Designing for Availability

Summary of Several Availability Studies
& Design Implications for LC Systems

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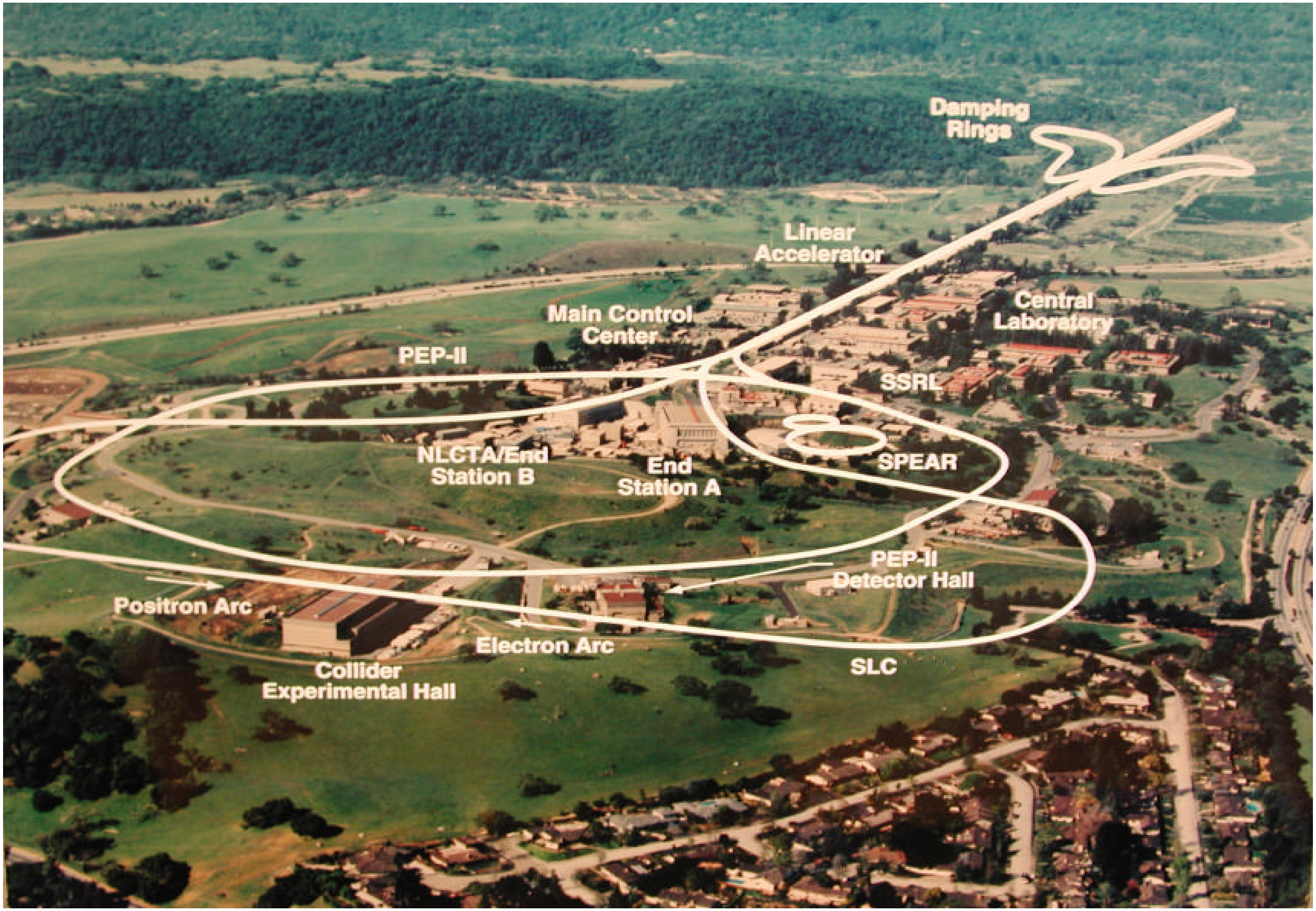
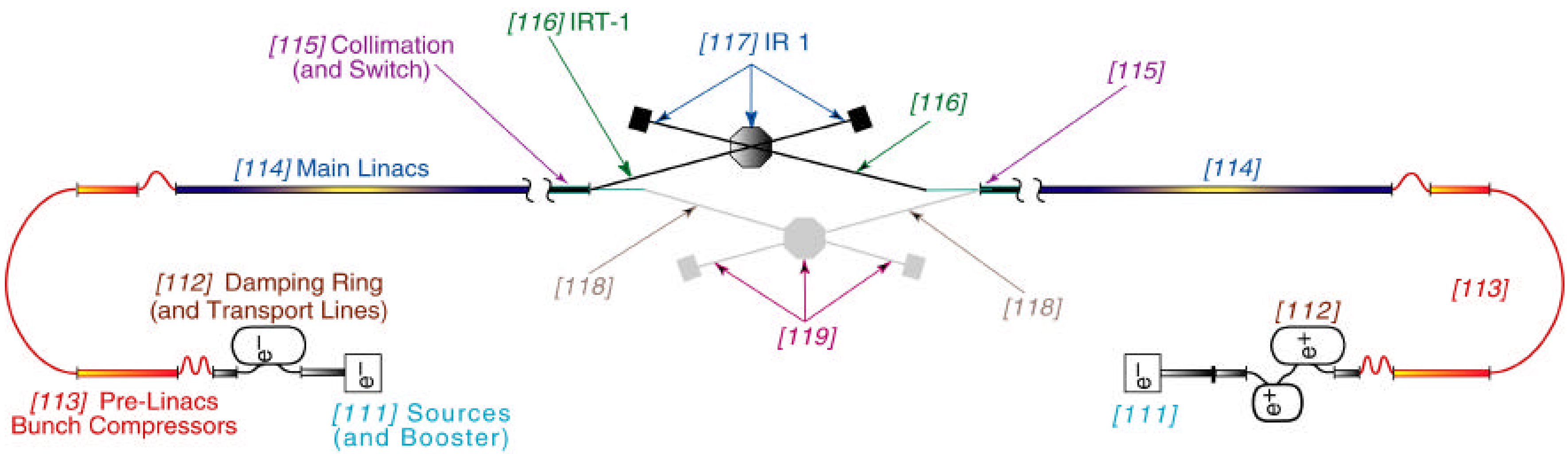
Scope

- Review existing NLC Availability model.
- Review Availability studies based on overall machine performance.
- Review specific studies of power supply & modulator systems.
- Discuss Availability goals for an LC and impact on new design approaches.

SLAC Machines



NLC System



NLC Beam Line Areas in the WBS

- Total of 6288 Klystrons for 2 Main Linac in 1 TeV operation (half for 500 Gev)
- Klystrons 75 MW RF output.
- Required System Availability for RF = .96
- Mission Time: 6575 hours (9 months)

Machine Availability

1. System Availability Model in NLC Zeroth Order Design Report (ZDR), May 1996, J. Sheppard et al

2. Power Supply Systems Studies, P. Bellomo et al, J. deLamare, 1999-2002

3. LC Power Supply System Availability Estimated from Measured Data for SLAC Machines, S. Rhee & C. Spencer, Sept 2002

4. SLC Modulator Upgrades, A.R. Donaldson, 1992-1999

5. Estimated Availability Solid State 8-Pack Modulator System, Z. Wilson, 1999

1. ZDR Availability Model

- Comparison made to SLC measured data & scaled
- LC Linac divided into 5 machines for e- and 7 for e+
  - 1. Source & Linac
  - 2. Damping Ring & Compressor
  - 3. Booster Linac & 2nd Compressor
  - 4. Main Linac
  - 5. Final Focus & Dumpline
  - 6. e+ Source & Linac
  - 7. e+ Damping Ring
- Eight Subsystems
  - Power supplies, Magnets, RF, Motors, BPMs, Controls, Utilities, Misc.

SLC Comparison

- Six machines.
- Similar complexity but fewer components per machine.
- Same eight subsystems.
- Subsystems given same weights for LC and SLC except Main Linac given 3X weight of other machines in each case.

Availability Goal (ZDR)

- Hrs/year scheduled operation = 6500
- Availability Goal = 85%
- Mean Time to Recover MTTR = 1 Hr
- Weighting: 3X for Main Linacs

Availability

- For NLC Model

  $Am=0.85^{**}\omega m/16$

  0.85 is overall system availability goal

  ωm = weight factor for given machine

  16 = sum of weight factors for 12 machines

  If MTTRs is 1 Hr (Mean system recovery time)

  Then mean time to system failure is

  MTTFs = MTTRs/(1-As)

  - Each of 12 machines must be available 99% time (97% for main linacs) to achieve 85% system availability.

LC Machine Weights & Availability Goals

Scheduled Operating Hours: 6500			
	Weight	Availability	Unscheduled Outage (hours)
e^- Inj, Source and Linac	1	0.99	66
e^- DR and Compressor 1	1	0.99	66
e^- Booster Linac and Comp. 2	1	0.99	66
e^- Main Linac	3	0.97	195
e^- Final Focus and Dumpline	1	0.99	66
Subtotal e^- machines:	**7**	**1**	**458**
e^- Inj, Source and Linac	1	0.99	66
e^+ Source and Linac	1	0.99	66
e^+ Pre-damping Ring	1	0.99	66
e^+ DR and Compressor 1	1	0.99	66
e^+ Booster Linac and Comp. 2	1	0.99	66
e^+ Main Linac	3	0.97	66
e^+ Final Focus and Dumpline	1	0.99	66
Subtotal e^+ machines:	**9**	**1**	**589**
Totals:	**16**	**0.85**	**1047**

Table 17-1. *Availability specifications for the NLC machines.*

LC Subsystem Availability Goals

NLC Systems	Availability	$MTTR_s$ (hours)	$MTTF_s$ (hours)	Unscheduled Outage (hours)
Power Supplies	0.975	1	40	163
Magnets	0.975	1	40	163
RF Systems	0.950	1	20	325
Motors	0.975	1	40	163
BPMs	0.990	1	100	65
Controls	0.985	1	67	98
Utilities	0.995	12	2400	33
Miscellaneous	0.995	1	200	33
Totals:	**0.85**			**1040**

Table 17-2. *Availability specification for the NLC systems.*

Collected Machine Availability Data

Laboratory	Availability	Reference
ANL (APS) 95	68.30%	Argonne National Lab., Private Communication, Site Visit – R. Gerig, D. Ciarlette
CERN (SPS) 94	69.30%	1994 SPS & LEP Machine Statistics CERN SL / Note 95–15 (OP) M. Colin, G. Cultrut and B. Desforges
CERN (SPS) 93	72.00%	1994 SPS & LEP Machine Statistics CERN SL / Note 95–15 (OP) M. Colin, G. Cultrut and B. Desforges
CERN (SPS) 92	74.00%	1994 SPS & LEP Machine Statistics CERN SL / Note 95–15 (OP) M. Colin, G. Cultrut and B. Desforges
CERN (SPS) 91	72.00%	1994 SPS & LEP Machine Statistics CERN SL / Note 95–15 (OP) M. Colin, G. Cultrut and B. Desforges
CERN (SPS) 90	74.00%	1994 SPS & LEP Machine Statistics CERN SL / Note 95–15 (OP) M. Colin, G. Cultrut and B. Desforges
CERN (SPS) 89	71.20%	1994 SPS & LEP Machine Statistics CERN SL / Note 95–15 (OP) M. Colin, G. Cultrut and B. Desforges
Fermi 91	72.64%	Fermi Accelerator System Tally Sheets, Site Visit – R. Mau
Fermi 92	65.86%	Fermi Acclerator System Tally Sheets, Site Visit – R. Mau
Fermi 93–94	63.71%	Fermi Acclerator System Tally Sheets, Site Visit – R. Mau
Fermi 93–94	63.71%	Fermi Acclerator System Tally Sheets, Site Visit – R. Mau
SLAC (SLC) 92	81.00%	1992 SLC Revealed Failure Tables, Internal SLAC Memo – W. Linebarger
SLAC (SLC) 93	84.53%	1993 SLC Revealed Failure Tables, Internal SLAC Memo – W. Linebarger
SLAC (SLC) 95	80.87%	1994/95 SLC Revealed Failure Tables, Internal SLAC Memo – W. Linebarger
SLAC (ESA) 92	87.01%	1992 SLC Revealed Failure Tables, Internal SLAC Memo – W. Linebarger
SLAC (ESA) 93	93.25%	1993 SLC Revealed Failure Tables, Internal SLAC Memo – W. Linebarger
SLAC (ESA) 94	93.33%	1994 SLC Revealed Failure Tables, Internal SLAC Memo – W. Linebarger
SLAC SSRL 94	97.04%	SSRL, Private Communication, Site Visit – E. Guerra
SLAC SSRL 95	96.60%	SSRL, Private Communication, Site Visit – E. Guerra
AGS, FY95Q3	86.30%	Brookhaven National Lab, FY 95 3rd Qtr. Report – F. Weng
AGS, FY94Q4	86.70%	Brookhaven National Lab, FY 94 4th Qtr. Report – F. Weng
Cornell 91–92	74.10%	CESR Reliability Summary FY 1992–FY 1994 – D. Rice
Cornell 92–93	77.90%	CESR Reliability Summary FY 1993–FY 1994 – D. Rice
Cornell 93–94	84.00%	CESR Reliability Summary FY 1994–FY 1994 – D. Rice
KEK Photon Factory Linac 10/92–9/93	98.70%	KEK Operations Report FY 1992–FY 1993
KEK Photon Factory Linac 10/91–9/92	98.40%	KEK Operations Report FY 1991–FY 1992
KEK Photon Factory Linac 10/90–9/91	97.70%	KEK Operations Report FY 1990–FY 1991

Table 17-3. *Availabilities of several accelerator laboratories.*

NLC vs. SLC Example Parts Counts

	Pwr sup	Magnets	Klystrons	Modulators	Motors	BPMs	Sys. Total
e^- Inj, Source and Linac	245	229	16	16	0	381	**887**
e^- DR and Compressor 1	817	709	5	5	300	555	**2391**
e^- Booster Linac and Comp. 2	452	482	116	116	1077	291	**2534**
e^- Main Linac	736	756	2264	1132	14643	5300	**24831**
e^- Final Focus and Dumpline	871	1466	1	1	1344	472	**4155**
e^- Inj, Source and Linac	244	229	40	40	0	381	**934**
e^+ Source and Linac	236	241	32	32	0	81	**622**
e^+ Pre-damping Ring	700	700	2	2	300	300	**2004**
e^+ DR and Compressor 1	817	709	5	5	300	555	**2391**
e^+ Booster Linac and Comp. 2	452	482	116	116	1077	291	**2534**
e^+ Main Linac	736	756	2264	1132	14643	5300	**24831**
e^+ Final Focus and Dumpline	871	1466	1	1	1344	472	**4155**
NLC Total	**7177**	**8225**	**4862**	**2598**	**35028**	**14379**	**72269**

Table 17-4. *Preliminary NLC parts count for several systems.*

	Pwr sup	Magnets	Klystrons	Modulators	Motors	BPMs	Sys. Total
e^- Inj, Source and Linac	249	247	16	16	10	37	**575**
e^- and e^+ DRs and Compressors	40	456	5	5	6	199	**711**
e^+ Source and Linac	30	452	2	2	5	204	**695**
e^- Main Linac	608	608	242	242	22	283	**2005**
SLC Arcs	119	1000	0	0	912	978	**3009**
SLC Final Focus	192	192	0	0	23	59	**466**
SLC Total	**1238**	**2955**	**265**	**265**	**978**	**1760**	**7461**

Table 17-5. *SLC parts count for several systems.*

2. Magnet Systems Reliability & Modeling

Refs: *NLC DC Magnet Power Supply Systems Review*, P. Bellomo, March 1999

B-Factory Magnet Systems Reliability Modeling and Results, P. Bellomo et al, PAC 2001.

Power Conversion Equipment Reliability at SLAC, Jeffrey deLamare, LC02, 2002.

PEP-II Availability Goals

- All Systems $\geq$76%
- All DC Magnet P.S. Systems $\geq$97%
- Intermediate P.S. Systems $\geq$98%

- There are 200 Intermediate P.S. Systems in PEP ranging from 2.5kW-17kW and assumed to run near their full rated power.

Some Terms Used to Calculate Reliability/Availability

MTBF = mean time between failures	*(hr)*
λ *= failure rate = MTBF*$^{-1}$	*(hr*$^{-1}$*)*
MTTR = mean time to repair/recover	*(hr)*
t = 9 month mission time = 6575 for LC	*(hr)*
Reliability = $e^{-\lambda t}$	*(none)*
Availability (A) = MTBF/(MTBF + MTTR)	*(none)*

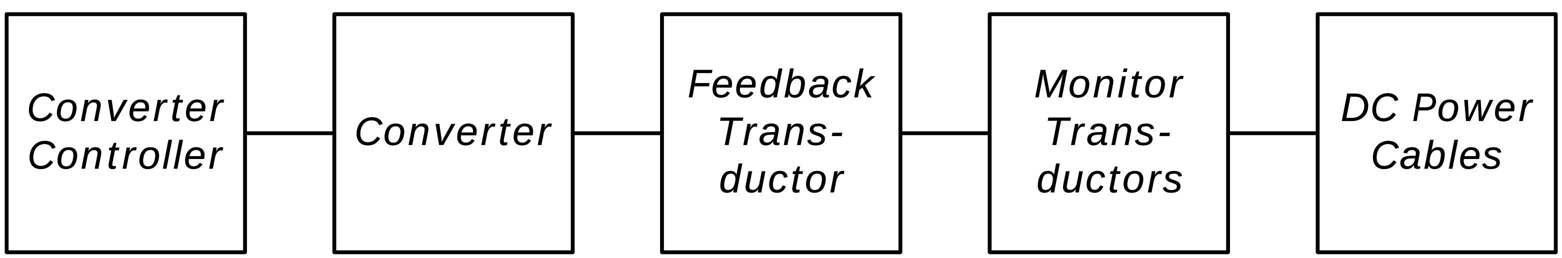
Intermediate P.S. Reliability Block Diagram

$$MTBF = \text{mean time between failures} \qquad (hr)$$

$$MTTR = \text{mean time to repair and recover} \qquad (hr)$$

$$t = \text{9 month mission time / year} = 6574 \qquad (hr)$$

$$Availability = A = \frac{MTBF}{MTBF + MTTR} \qquad (none)$$



Calculated Single & 200 System Availabilities

Single System Availabilty

Component	MTBF	Availability
Controller	110,000	0.9999818
Converter	60,000	0.9999667
Transductor 1	381,500	0.9999948
Transductor 2	381,500	0.9999948
Cables	14,000,000	0.9999999
System	32,184	0.9999379

200 System Availability

$$MTBF_{200} = 160.9 \text{ hours}$$

$$A_{200} = A_1^{200} = 0.9999379^{200} = 0.9876564$$

t=6574 hrs/year MTTR=2 hrs components/system

Two-Year Operating Results (6/99-6/01)

Component	MTTR Hrs	Failures	MTBF Hrs	Availability
			1 System	
Controller	2	9	288,889	0.9999931
Converter	2	102	25,490	0.9999215
Transductor 1	4	2	1,300,000	0.9999969
Transductor 2	4	2	1,300,000	0.9999969
Cables	12	1	2,600,000	0.9999954
System		116	22,414	0.9999039
			200 Systems	
Controller			1,444	0.9986173
Converter			127	0.9845501
Transductor 1			6,500	0.9993850
Transductor 2			6,500	0.9993850
Cables			13,000	0.9990778
System			112	0.9811321

PEP-II Injector Availability (10/98-10/00)

Injector MTBF	**21.91**		**Scheduled Operating Hrs**	**12771.00**
Injector MTTR	**2.26**		**Total Events**	**583**
Injector Availability	**89.68%**		**Total Hrs down**	**1317.60**

Subsystem Data						Area Data					
System	Events	Hrs Down	MTBF	MTTR	Av. (%)	Area	Events	Hrs Down	MTBF	MTTR	Av. (%)
Power Supplies	142	254.3	89.94	1.79	98.05	Inj/S0&1	94	204.50	135.86	2.18	98.42
Magnets	29	211.75	440.38	7.30	98.37	NDR	69	181.55	185.09	2.63	98.60
RF	75	120.9	170.28	1.61	99.06	SDR	73	197.55	174.95	2.71	98.48
Vacuum	42	45.3	304.07	1.08	99.65	Linac	165	237.80	77.40	1.44	98.17
Utilities	68	250.95	187.81	3.69	98.07	E+	47	123.80	271.72	2.63	99.04
Cryogenics	1	2.5	12771.00	2.50	99.98	BSY	32	102.60	399.09	3.21	99.20
Controls	156	280.2	81.87	1.80	97.85	PEPII-Inj	19	50.50	672.16	2.66	99.61
Safety	2	1.9	6385.50	0.95	99.99	SARC	2	3.00	6385.50	1.50	99.98
Other	68	149.85	187.81	2.20	98.84	MCC	42	77.50	304.07	1.85	99.40
						Other	40	138.80	319.28	3.47	98.92
Totals	**583**	**1317.65**					**583**	**1317.60**			

PEP-II Ring Availability (10/98-10/00)

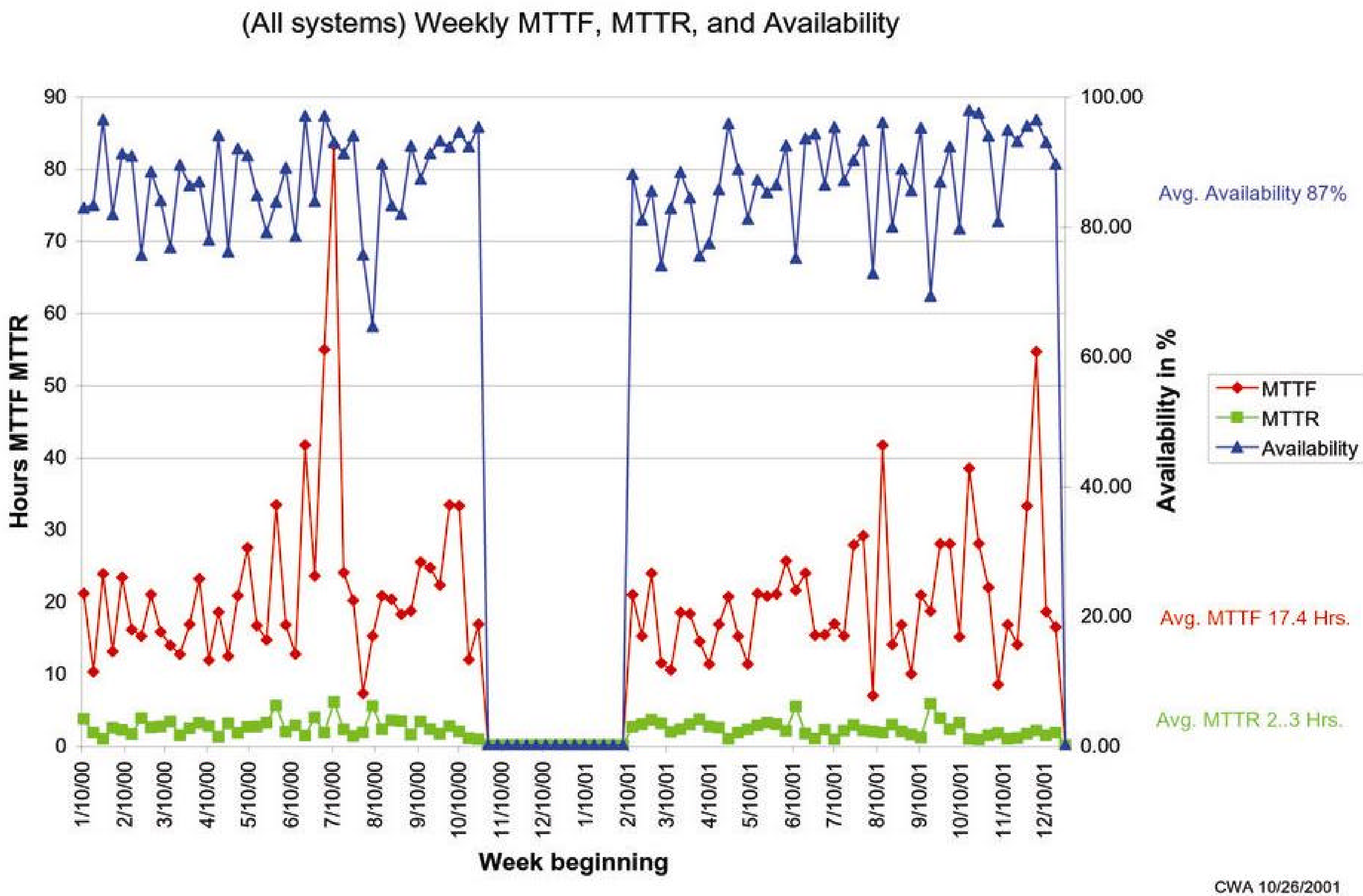
PEP MTBF		**34.69**				**Scheduled Operating Hrs**			**12730.80**		
PEP MTTR		**2.67**				**Total Events**			**367**		
PEP Availability		**92.30%**				**Total Hrs down**			**980.75**		
Subsystem Data								**Area Data**			
System	**Events**	**Hrs Down**	**MTBF**	**MTTR**	**Av. (%)**	**Area**	**Events**	**Hrs Down**	**MTBF**	**MTTR**	**Av. (%)**
Power Supplies	128	283.15	99.46	2.21	97.82	HER	241	624.15	52.82	2.59	95.33
Magnets	10	32.7	1273.08	3.27	99.74	LER	126	356.60	101.04	2.83	97.28
RF	85	219.9	149.77	2.59	98.30						
Vacuum	14	167	909.34	11.93	98.71						
Utilities	26	84.6	489.65	3.25	99.34						
Cryogenics	1	1.4	12730.80	1.40	99.99						
Controls	82	152.8	155.25	1.86	98.81						
Safety	1	2.8	12730.80	2.80	99.98						
Other	20	36.4	636.54	1.82	99.71						
Totals	**367**	**980.75**					**367**	**980.75**			

PEP-II Availability (10/98-10/00)

PEPII MTBF	**14.92**		**Scheduled Operating Hrs**	**12771.00**	
PEPII MTTR	**2.55**		**Total Events**	**856**	
PEPII Availability	**82.89%**		**Total Hrs down**	**2185.70**	

Subsystem Data / **Area Data**

System	Events	Hrs Down	MTBF	MTTR	Av. (%)	Area	Events	Hrs Down	MTBF	MTTR	Av. (%)
Power Supplies	254	525.65	50.28	2.07	96.05	Inj/S0&1	65	172.90	196.48	2.66	98.66
Magnets	35	210.35	364.89	6.01	98.38	NDR	68	181.05	187.81	2.66	98.60
RF	141	319.4	90.57	2.27	97.56	SDR	71	196.35	179.87	2.77	98.49
Vacuum	47	210.8	271.72	4.49	98.38	Linac	117	187.50	109.15	1.60	98.55
Utilities	85	321.95	150.25	3.79	97.54	E+	43	112.30	297.00	2.61	99.13
Cryogenics	2	3.9	6385.50	1.95	99.97	BSY	17	52.70	751.24	3.10	99.59
Controls	217	405.6	58.85	1.87	96.92	ESA	8	14.80	1596.38	1.85	99.88
Safety	5	9.2	2554.20	1.84	99.93	PEPII-Inj	19	50.50	672.16	2.66	99.61
Other	70	178.85	182.44	2.56	98.62	SARC	1	2.40	12771.00	2.40	99.98
						HER	241	624.15	52.99	2.59	95.34
						LER	126	356.60	101.36	2.83	97.28
						MCC	34	64.05	375.62	1.88	99.50
						Other	37	137.20	345.16	3.71	98.94
						FFTB	9	33.20	1419.00	3.69	99.74
Totals	**856**	**2185.7**					**856**	**2185.70**			



(All systems) Weekly MTTF, MTTR, and Availability
Hours MTTF MTTR
Availability in %
Week beginning
Avg. Availability 87%
Avg. MTTF 17.4 Hrs.
Avg. MTTR 2..3 Hrs.
MTTF
MTTR
Availability
CWA 10/26/2001

January 10, 2000 to December 31, 2001 Revealed Failures (All systems)

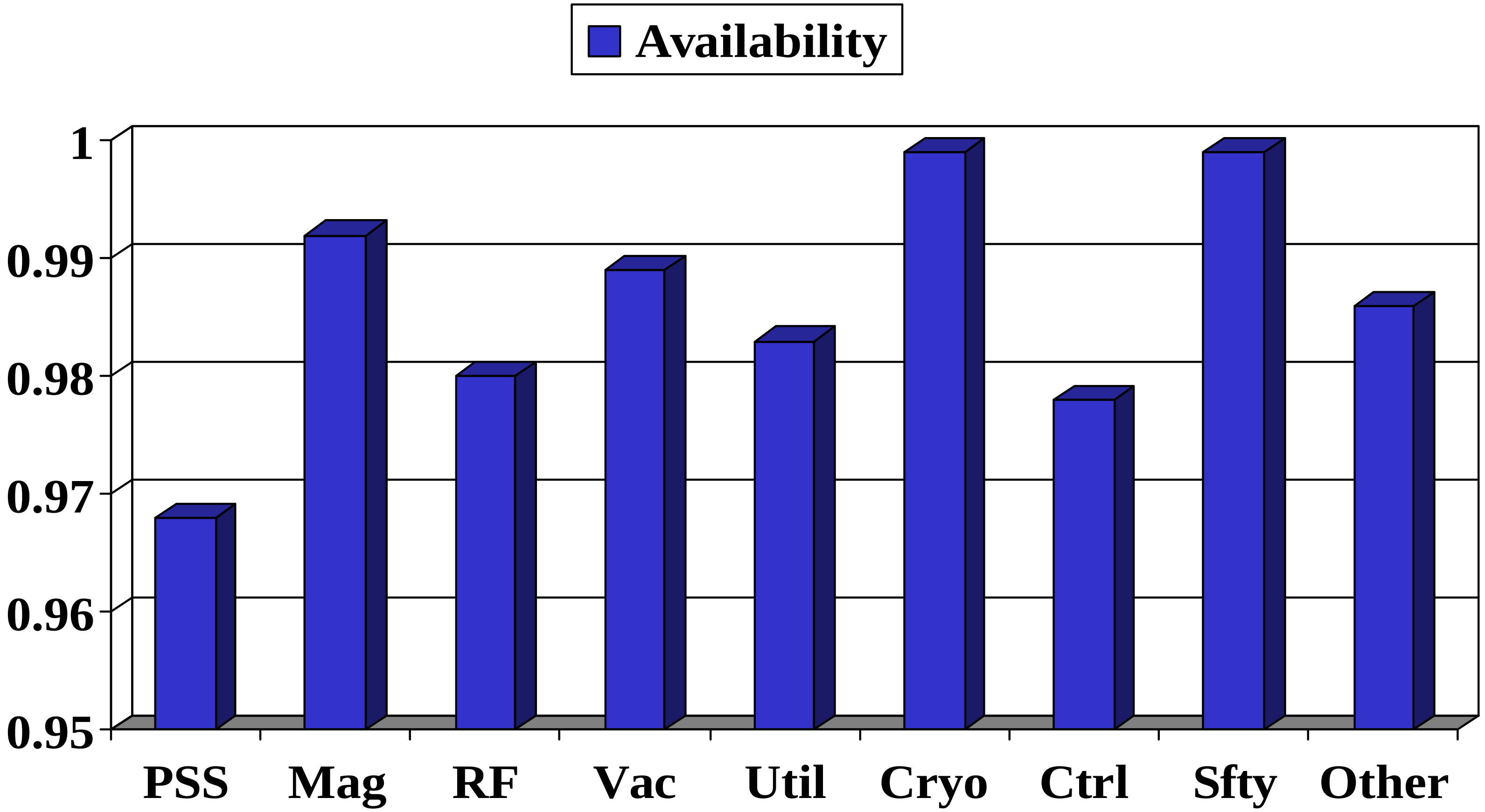
MTTF	**17.4**		**Scheduled Operating Hrs**	**13698.60**
MTTR	**2.3**		**Total Events**	**788**
Availability	**87%**		**Total Hrs down**	**1773.10**

Scheduled Operating Hrs = 14616 - Scheduled Outage

Scheduled Outage 917.4

Subsystem Data					Area Data				
System	Events	Hrs Down	MTTF	MTTR	Area	Events	Hrs Down	MTTF	MTTR
Power Supplies	234	459.8	58.54	1.96	Inj/S0&1	48	145.10	285.39	3.02
Magnets	27	111.9	507.36	4.14	NDR	60	159.00	228.31	2.65
RF	137	278.15	99.99	2.03	SDR	59	154.95	232.18	2.63
Vacuum	44	155.9	311.33	3.54	Linac	97	143.35	141.22	1.48
Utilities	96	244.25	142.69	2.54	E+	38	73.00	360.49	1.92
Cryogenics	2	15.6	6849.30	7.80	PEPII/Inj	20	38.00	684.93	1.90
Controls	180	308.3	76.10	1.71	BSY	12	16.90	1141.55	1.41
Safety	3	9.45	4566.20	3.15	HER	234	453.30	58.54	1.94
Other	65	189.75	210.75	2.92	LER	128	342.80	107.02	2.68
					ESA	1	3.00	13698.60	3.00
					MCC	21	34.85	652.31	1.66
					Other	69	207.45	198.53	3.01
					FFTB	1	1.40	13698.60	1.40
Totals	**788**	**1773.10**	**17.38**	**2.25**		**788**	**1773.10**	**17.38**	**2.25**

PEPII System Availability 00-01



Question: How can we connect component performance and system uptime?

- Must have an easily searchable database where system uptime, component failure records, and repair time data are stored.
- Must make the collection of system performance data a high priority.

PSS 2/3 Configuration - The Background

For 500GeV Initial Operation

40V, 125A, 5kW	40V, 125A, 5kW	

K=2, N=1

For 1000GeV Final Operation

40V, 125A, 5kW	40V, 125A, 5kW	40V, 125A, 5kW

K=3, N=2

Reliability Notes And Assumptions

1. Mission time is t = 6575 hours.

2 All power supplies are parallelable, but not hot-swappable. Mean time to repair/replace (MTTR) = 2 hours.

3. MTBF = 60,000 hrs, invariant of rating because:
5kW to 20kW is relatively narrow power range.
Switchmode power supplies, delivering their rated power.
Operating in same environment.
Have been designed with the same topology and component stress factors.

4. MTBF at reduced power equals MTBF at rated power times the ratio of the rated to reduced power.

5. The reliability statistics do not include the PS controllers, transductors,etc.

6. K = Total quantity of ps in a PSS. N = Number of ps that must be operational.

Some More Notes

$$MTBF_{psrap} = 1/\,l_{psrap}$$

$$MTBF_{psrep} = MTBF_{psrap} * (RAP\,/\,REP)$$ rap = rated power rep = reduced power

$$l_{psrep} = 1/\,MTBF_{psrep}$$

R = Reliabilit y

$$R_{pss} = e^{-l\,psrep*t}$$ for a system with 1 ps

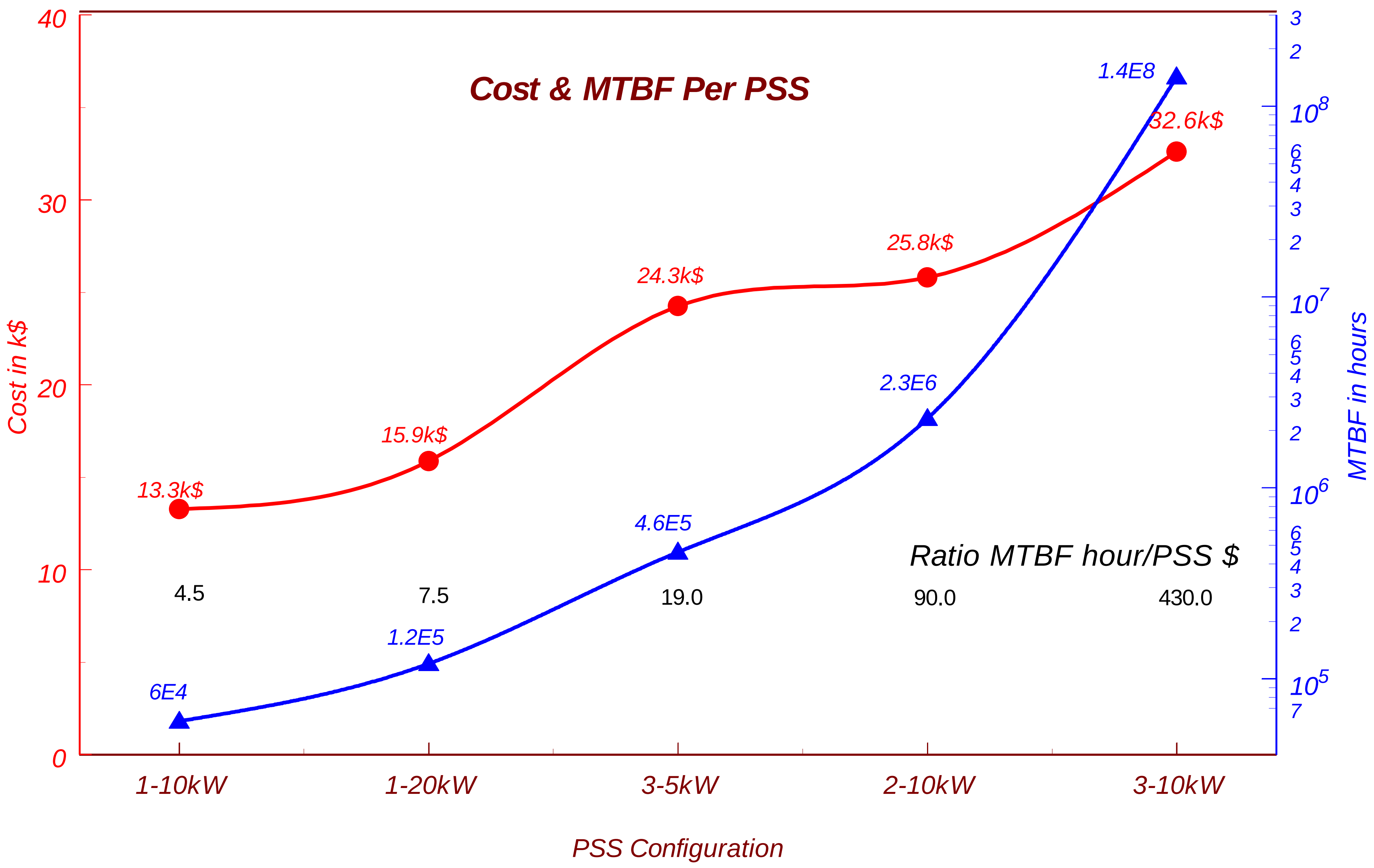
$$R_{pss} = K\,e^{-N*l\,psrep*t} - N\,e^{-K*l\,psrep*t}$$ for a multiple ps pss

$$MTBF_{pss} = -t/\ln(R_{pss}) \qquad l_{pss=1/MTBF_{pss}}$$

$$MTBF_{1500\;pss=1/(1500*l_{pss}})$$

$$A_{pss} = MTBF_{pss}/(MTBF_{pss} + MTTR_{pss})$$

$$A_{1500\;pss} = A_{pss}^{1500}$$

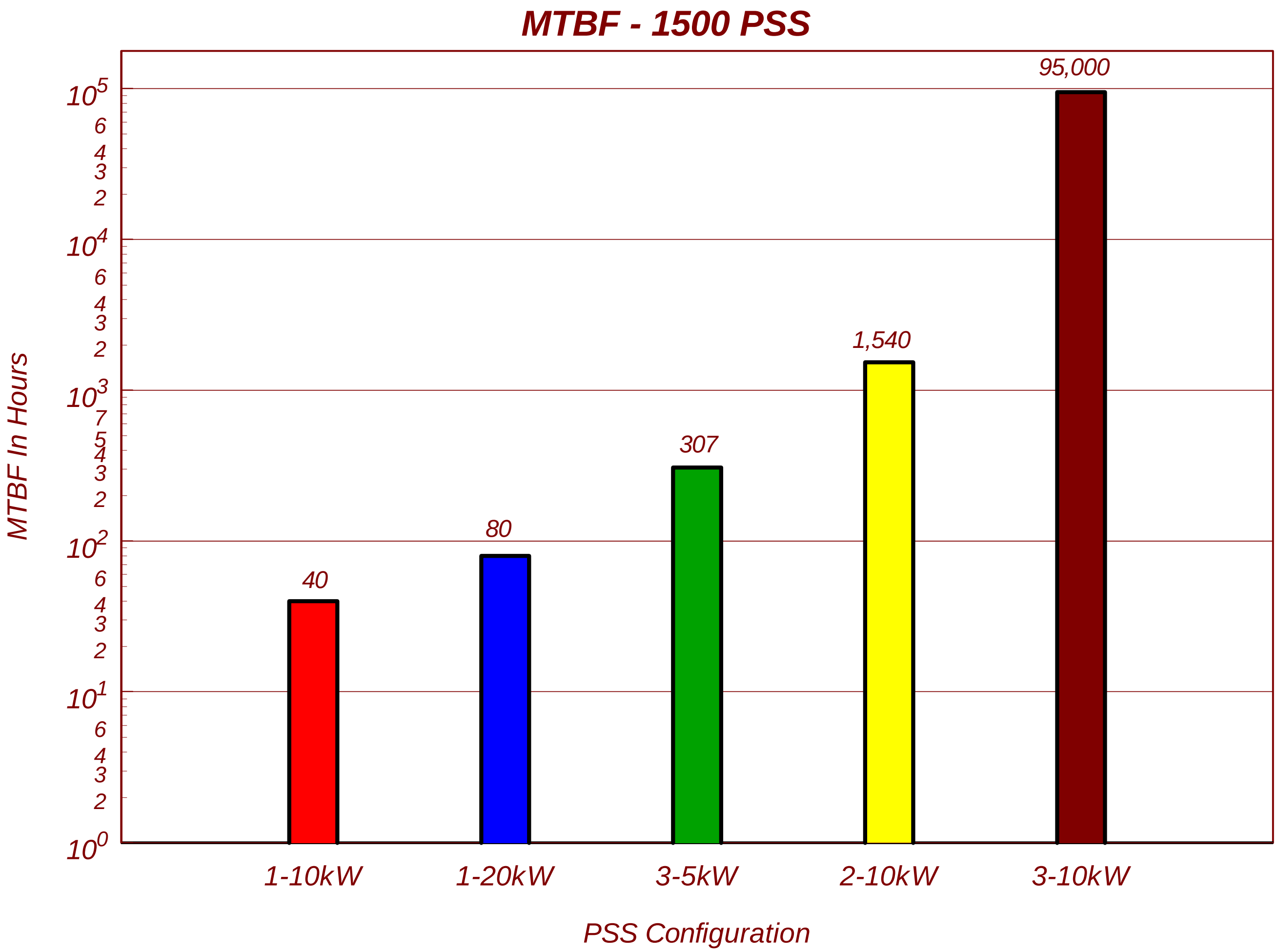


Cost & MTBF Per PSS
Cost in k$
MTBF in hours
13.3k$
15.9k$
24.3k$
25.8k$
32.6k$
6E4
1.2E5
4.6E5
2.3E6
1.4E8
Ratio MTBF hour/PSS $
4.5
7.5
19.0
90.0
430.0
1-10kW
1-20kW
3-5kW
2-10kW
3-10kW
PSS Configuration

Redundancy: Cost and Reliability Summary

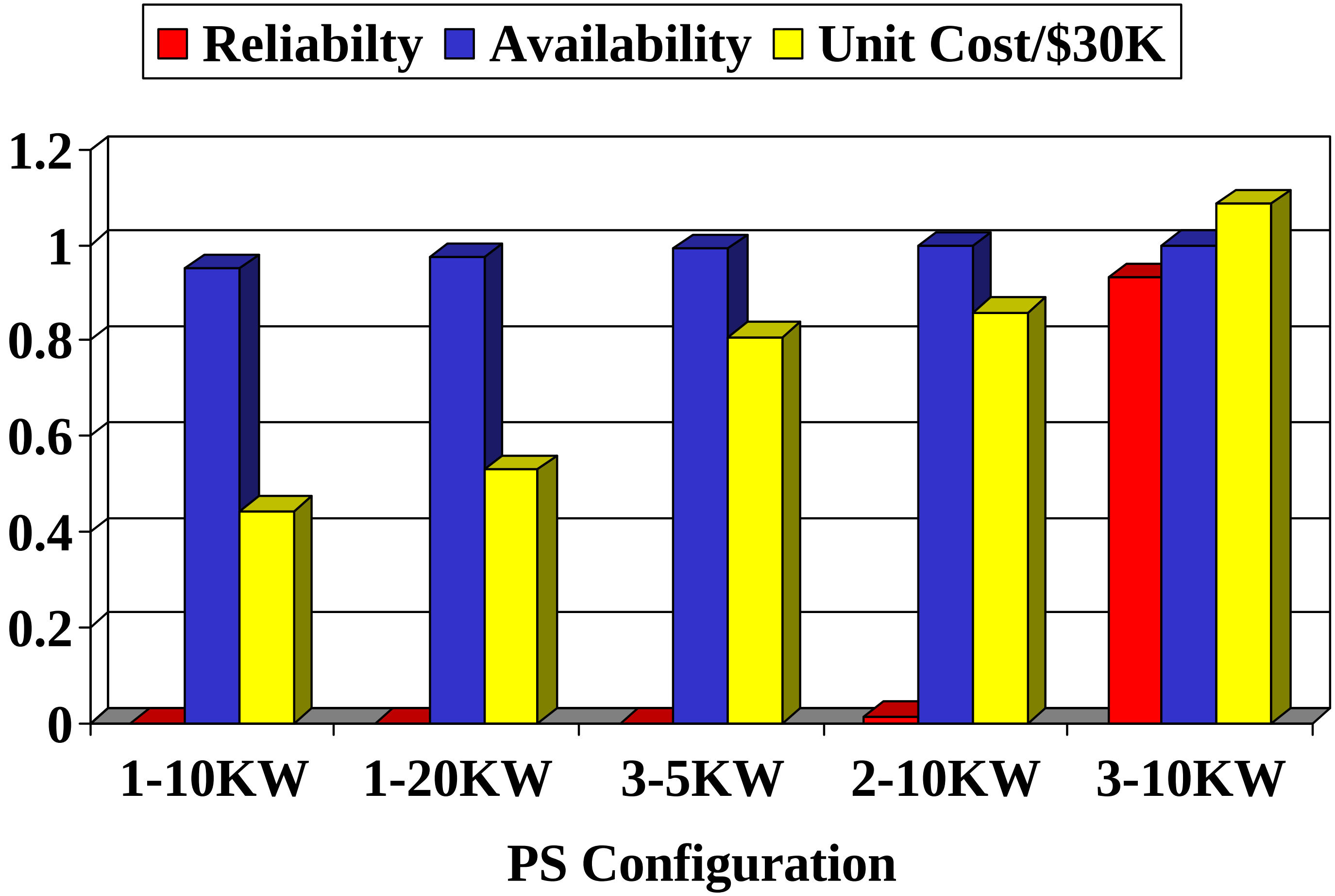
PSS Configuration	Cost	MTBF Per PSS	MTBF Per 1500PSS	Reliability Per PSS	Reliability Per 1500PSS	Availability Per PSS	Availability Per 1500PSS
1-10kW	$13,289	60,000	40	0.896207	0.000000	0.999967	0.951230
1-20kW	$15,886	120,000	80	0.946682	0.000000	0.999983	0.975310
3-5kW	$24,258	461,000	307	0.985836	0.000000	0.999996	0.993514
2-10kW	$25,808	2,310,000	1,540	0.997158	0.013989	0.999999	0.998702
3-10kW	$32,616	142,500,000	95,000	0.999954	0.933130	1.000000	0.999979

Redundancy: MTBF vs. P.S. Configuration



10kW 1500 PSS Configuration Example

Mission Time 6575 Hrs. MTTR 2 Hrs. [Ref. P. Bellomo]



3. Ongoing Power Supply System Studies

Estimated Magnet Power Supply System Availability for the NLC Using SLAC Failure Data

S. Rhee & C. Spencer, Sept. 2002

(Private Information from Study in Progress)

Estimating Magnet Power Supply Availability for the NLC Using SLAC Failure Data

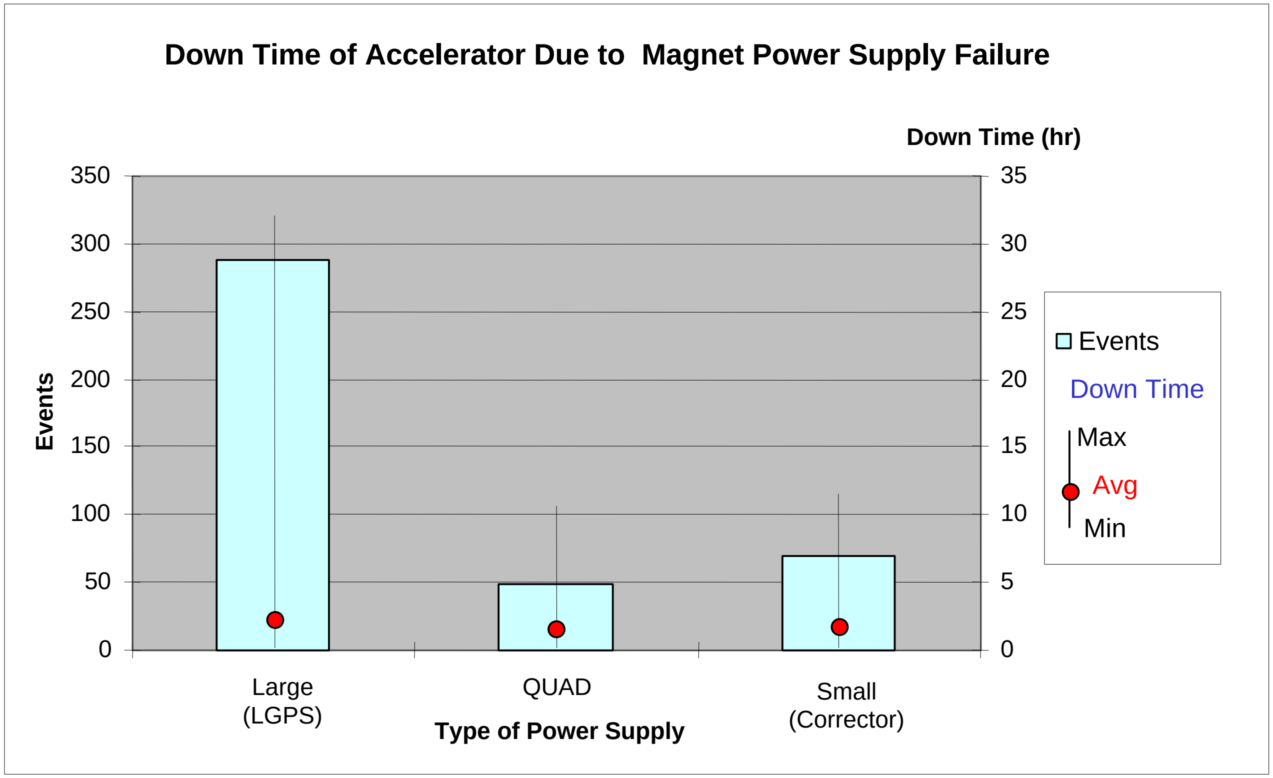
1. Obtain failure history (CATER system) for 5 year period (1997-2001)
2. Categorize data into Large Power Supply (PS) and Corrector Power Supply (PS) types, then further identify switching and non-switching types.
3. Calculate average downtime for different types of PS from failure data.
4. Obtain SLAC runtime schedule for this 5 year period
5. Count number of PS in each SLAC beam-line during specific runtime periods.
6. Identify PS failures that shut down the beam from CATER system report for each runtime period.
7. Calculate PS operating hours by multiplying number of PSs and run hours for each period.
8. Calculate MTBF and availability of one PS for each period.
9. Calculate average availability for the PS, and assume NLC PS will have the same availability.
10. Availability of the NLC PSs is obtained by raising the availability of an individual PS to the power of the total number of PSs for the NLC.

Assumptions

1. Two sizes for the switching PS were considered :
   1) Small (~12A/50V): Corrector type
   2) Large (Anything larger)
2. Only failures that required any SLAC beamline to shut down were considered in calculating availability.
3. Boards will be replaced by new ones. (Material cost: $500/board)
4. Labor cost is assumed at $65/hr for 2 operators to find and switch the boards in 1.65 hours.
5. Having redundant PS has not been considered at this stage.
6. 3 Months of maintenance shut down time per year is assumed in the calculation.

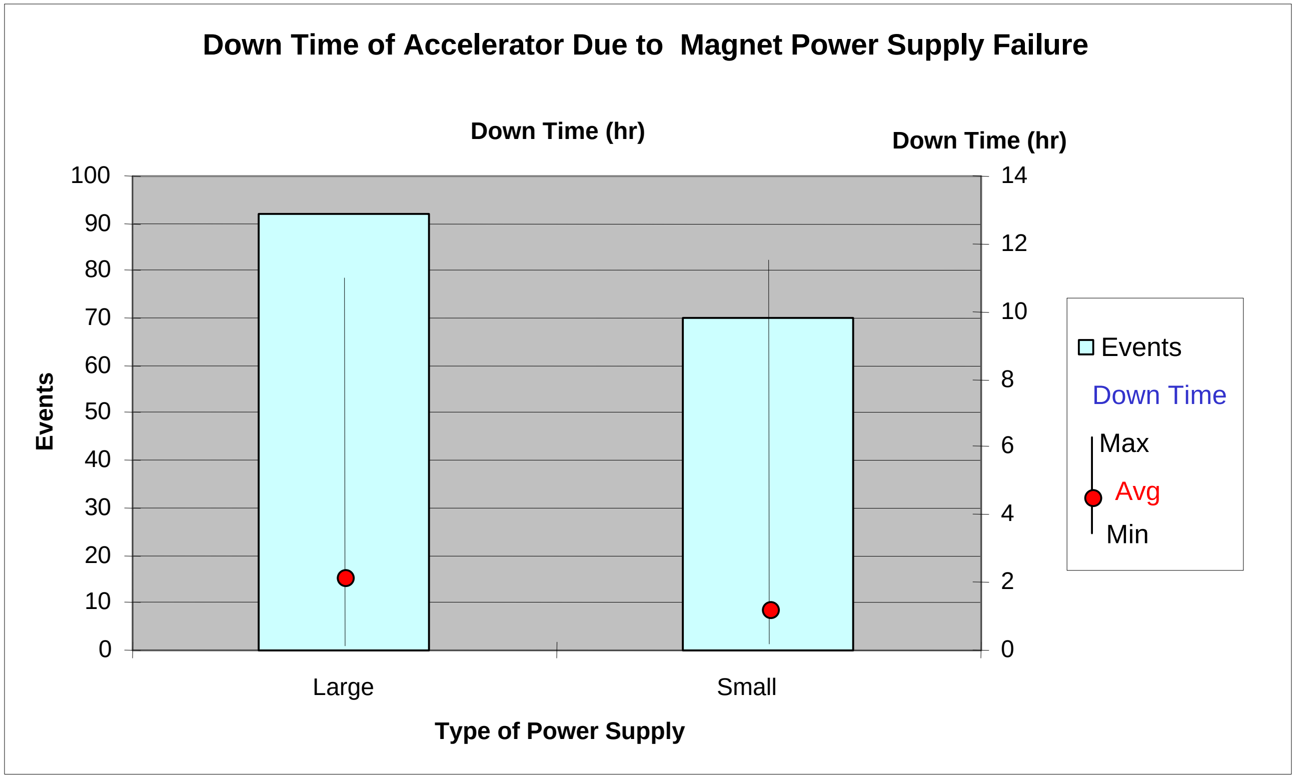
at SLAC (*All Types of PS*)

Type of PS	Events	Total Down Time	Max	Min	Avg Down Time
LGPS	288	580.6	32	0.1	2.01
QUAD	48	72	10.7	0.1	1.5
X&Y COR	70	88.7	11.5	0.2	1.27
Total	406	741.3	32	0.1	1.82
					Units: Hour



Magnet Power Supply Failure: Jan 97 to Dec 2001 at SLAC *(Switching Type PS)*

Type of PS	Events	Total Down Time	Max	Min	Avg Down Time
Large	92	178	11	0.1	1.93
Small	70	88.7	11.5	0.2	1.27
Total	162	266.7	32	0.1	1.65
					Units: Hour



Estimating Availability for Small Magnet PS (< 12A, 50V) for NLC

Power Supply Failures (Small)

Date	Line	Run Hour	Power Supply	PS Hours	# Failures	MTBF	TR	MTTR	Availability of 1 PS	PPM
2/4/97 - 4/30/97	Linac/BSY	1547	52	132572	2	66286	1.5	0.75	0.9999887	11.3
	HER	181	288							
5/1/97 - 6/8/98	SLC	8828	62	811720	26	31220	37.15	1.43	0.9999542	45.8
	HER	918	288							
7/10/98 - 7/31/98	HER&LER	575	907	521525	1	521525	1.5	1.50	0.9999971	2.9
10/30/98 - 12/15/98	HER&LER	1040	907	943280	3	314427	5.7	1.90	0.9999940	6.0
1/15/99 - 2/22/99	HER&LER	844	907	765508	6	127585	15.1	2.52	0.9999803	19.7
2/24/99 - 5/1/99	Linac	1461	52	75972	1	75972	0.5	0.50	0.9999934	6.6
5/1/99 - 11/29/99	HER&LER	4797	907	4350879	9	483431	4.1	0.46	0.9999991	0.9
1/12/00 - 10/31/00	HER&LER	6624	907	6078024	10	607802	14.5	1.45	0.9999976	2.4
	BSY/FFTB	2196	21							
	BSY/A-Line	630	38							
1/10/01 - 12/31/01	HER&LER	7411	907	6811632	12	567636	8.7	0.73	0.9999987	1.3
	BSY/FFTB(e+)	2795	21							
	BSY/A-Line	820	38							
Average				20,491,112	70	292,730	88.75	1.27	0.9999957	4.3
		# of PS				PPM				
	NLC	2785		Availability	0.98801024	11,989.76				
	PEP II	907		Availability	0.99607936	3,920.64			HER + LER = PEP II	
	Forecast for NLC									
	Operation Hr/yr	6480								
	Expected Downtime	**77.7**	hr/year							
	Occurrence/yr	**61.3**		**MTBF**	**105.7**	hours				

Estimating Availability for Large Magnet PS (> 12A, 50V) for NLC

Power Supply Failures (Large)

Date	Line	Run Hour	Power Supply	PS Hours	# Failures	MTBF	TR	MTTR	Availability for 1 PS
2/4/97 - 4/30/97	Linac/BSY	1547	51	89033	0	159341	0	0.00	1.0000000
	HER	181	56						
5/1/97 - 6/8/98	SLC	8828	95	890068	5	178014	10.3	2.06	0.9999884
	HER	918	56						
7/10/98 - 7/31/98	HER&LER	575	425	244375	7	34911	15	2.14	0.9999386
10/30/98 - 12/15/98	HER&LER	1040	425	442000	8	55250	23.1	2.89	0.9999477
1/15/99 - 2/22/99	HER&LER	844	425	358700	7	51243	17.9	2.56	0.9999501
2/24/99 - 5/1/99	Linac	1461	51	74511	0	150483	0	0.00	1.0000000
5/1/99 - 11/29/99	HER&LER	4797	425	2038725	18	113263	49.5	2.75	0.9999757
1/12/00 - 10/31/00	HER&LER	6624	425	2821500	24	117563	28.4	1.18	0.9999899
	BSY/FFTB	2196	0						
	BSY/A-Line	630	10						
1/10/01 - 12/31/01	HER&LER	7411	425	3157875	27	116958	45.9	1.70	0.9999855
	BSY/FFTB(e+)	2795	0						
	BSY/A-Line	820	10						
Average				10,116,787	96	105,383	190.10	1.98	0.9999812

		# of PS				PPM			
	NLC	3382		Availability	0.93842809	61,571.91			
	PEP II	425		Availability	0.99204589	7,954.11			HER +LER PEP II
	Forecast for NLC								
	Operation Hr/yr	6480							
	Expected Downtime	399.0	hr/year						
	Occurrence/yr	201.5		**MTBF**	32.2	hours			

Estimating Availability for All PS for NLC *(Assuming Switching Type)*

Availability = Small PS Availability x Large PS Availability
= 0.98801 x 0.93843 = **0.92718**

Expected Downtime = (1-Availability) x Operation hour/year
= 0.07282 x 6480 hour/year
= **471.9 hour/year**

Occurrence = Expected Downtime / MTTR
= 471.9 / 1.65 = **286 / year**

MTBF = Operation hour / Occurrence
= 6480 / 286 = **22.6 hours**

Results

Expected Downtime Assuming no Redundancy

Small PS:	**78 hr / yr**
Large PS:	**400 hr / yr**
TOTAL :	**478 hr / yr**

Expected PS Failure Cost (Labor + Material)

	Small	Large	1 yr Total	30 yr Total
Failure Occurrence / yr	61	201	**262**	
Material Cost	$ 30,500	$ 100,500	**$ 131,000**	**$ 3,930,000**
Labor Cost	$ 13,085	$ 43,115	**$ 56,199**	**$ 1,685,970**
Material + Labor	$ 43,585	$ 143,615	**$ 187,199**	**$ 5,615,970**

Assuming no redundancy

Opportunity Cost

Expected Lost Opportunity Cost at 478 hrs Lost Beam Time/yr

Opportunity cost/ hour	1 yr	30 yrs
$ 10k	$4.8	$144M
$ 25k	$11.9M	$358M
$ 50k	$23.9M	$717M

MTBF for the NLC System of power supplies

Assuming no redundancy

Small PS: 105.6 hr

Large PS: 32.2 hr

4. SLC Modulator Upgrade

Ref: SLAC Modulator System Improvements and Reliability Results

A.R. Donaldson, 1999

SLAC Publication

TABLE I: SLC Klystron-modulator Deployment

LOCATION	QUANTITY	E [GeV]
Injector Stations	5	0.2
Sector 1 Stations	5	1.15
N & S Damping Rings:		1.15
NRTL Compressor #	1	
SLTR Compressor #	1	
SRTL Compressor #	1	
Sectors 2 to 18 Stations	135	32.8
Sector 19 Stations	7	34.5
Positron Source:		
e^- to Target Station #	1	30.5-31.5
e^+ Accelerate Station #	1	0.2
Sector 20 Stations	7	36
Sectors 21 to 30 Stations	80	55
Energy to SLC Arcs		47
Energy to SLD Detector		46
Total Station Count	244	

TABLE II: Klystron and Modulator Characteristics

Klystron Peak Power Out	67	MW
RF Pulse Width	3.5	μs
Klystron Beam Voltage	350	kV
Klystron Beam Current	414	A
Modulator Peak Power Out	150	MW
Repetition Rate	120	Hz (max)
Thyratron Anode Voltage	46.7	kV
Thyratron Anode Current	6225	A
Pulse Transformer Ratio	1:15	
Voltage Pulse Width	5.0	μs (ESW)
Pulse Flattop Ripple	±0.25	%
Nominal PFN Impedance	4	Ω
Total PFN Capacitance	0.70	μF

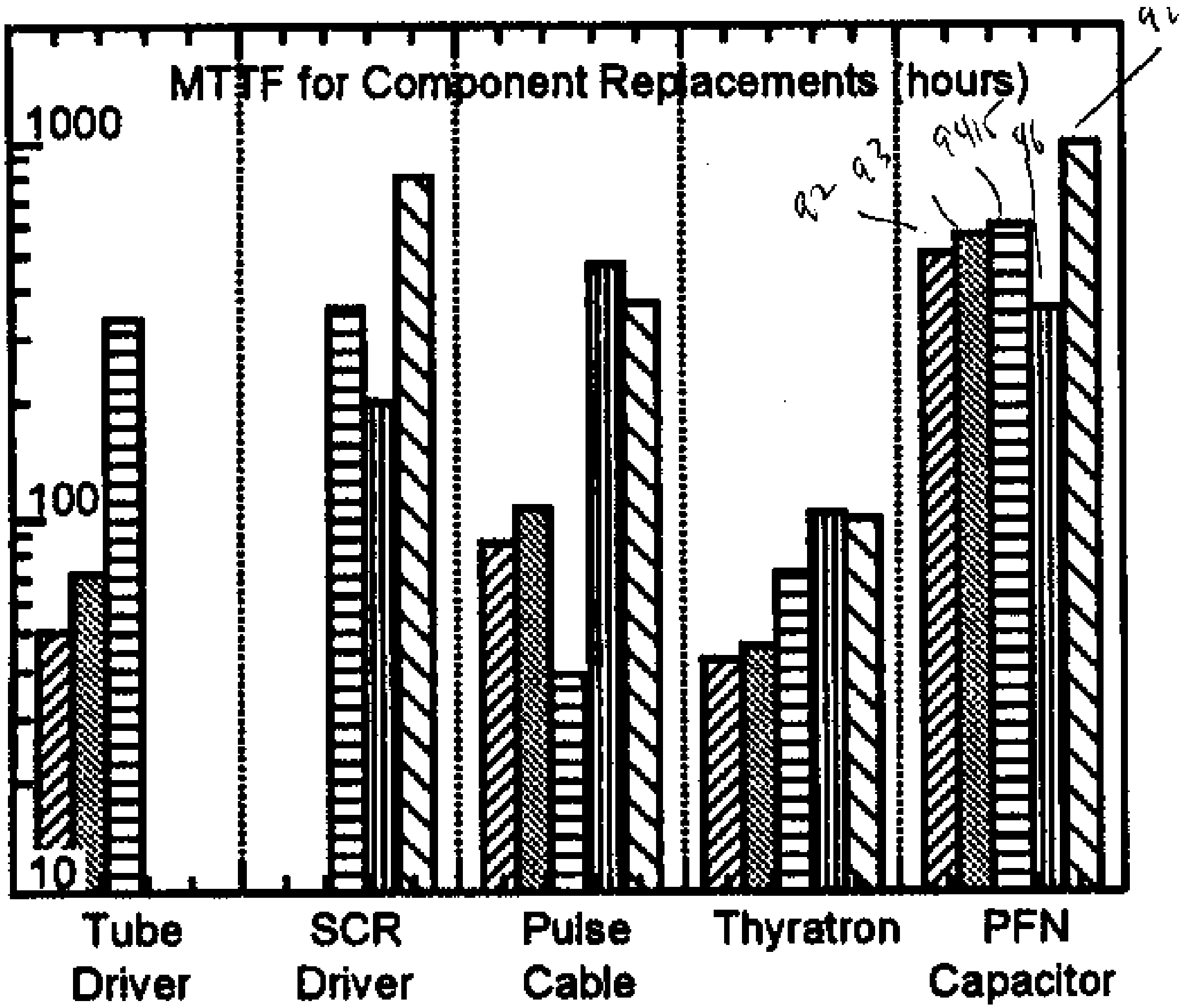


Figure 1. MTTF for five modulator components based on five operating periods.

TABLE A-I: System and Modulator Data for Five Runs

	244 System	15 Critical	
SLC Operating Period	28,219	28,219	Hr
SLC/Modulator-hours	6.88 e6	4.23 e5	
No. of Interventions	10,889	549	
Total Repair Time	4,314	222	Hr
System Failure Rate	0.386	0.019	P/hr
System MTTF	2.6	52.6	Hr
Modulator MTTF	632	771	Hr
Modulator MTTR	0.396	0.404	Hr
System "Availability"	0.847	0.992	
System "A" w/ Spares	0.931	not applicable	

TABLE A-2: Reliability and Availability of Modulators

Run Period	1992	1993	94/5	1996	97/8
PRR (Hz)	120	120	120	120	120
Operating Hr	5568	5736	6070	2841	8004
244 Sys Interv.	2670	2095	1899	1358	2867
244 Sys MTTR	0.383	0.382	0.437	0.387	0.396
244 Sys MTTF	509	668	780	510	681
244 Sys "A"	0.816	0.860	0.863	0.815	0.858
15 Critical "A"	0.995	0.996	0.992	0.982	0.991

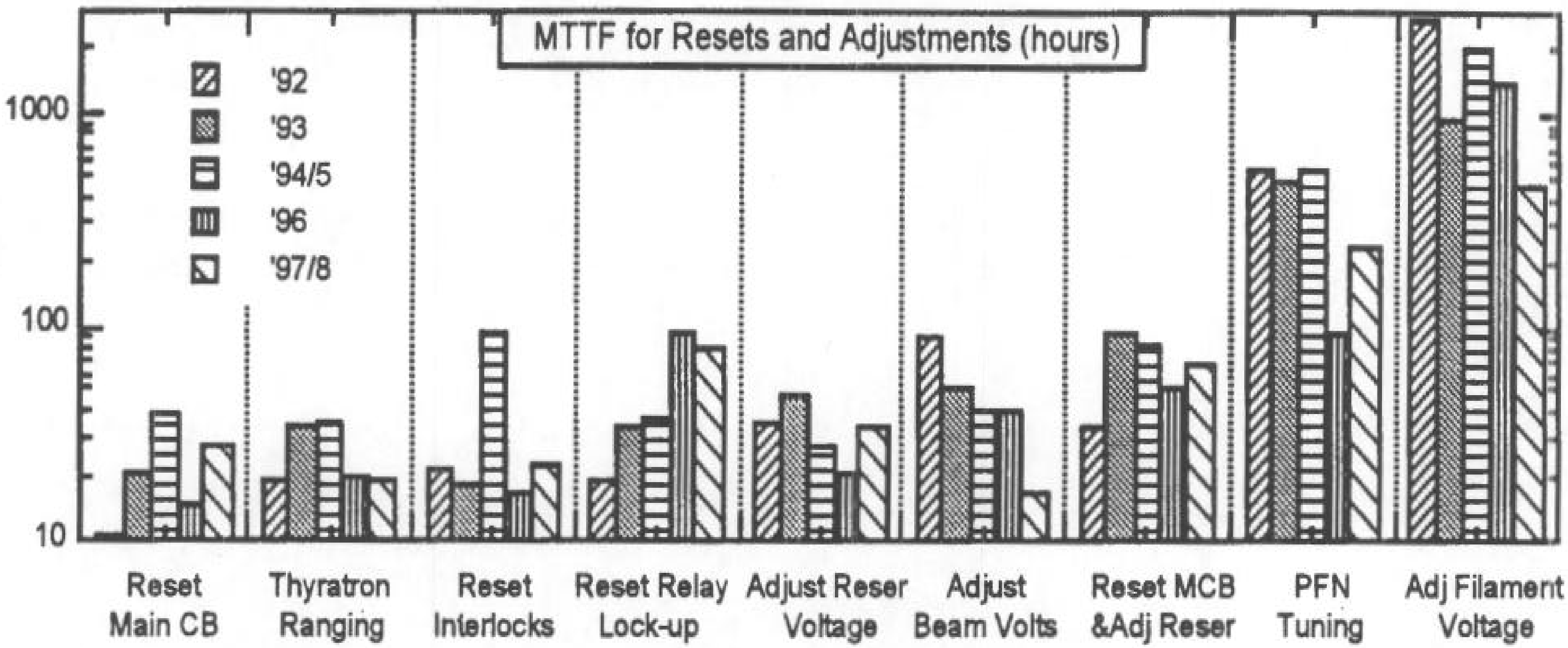


Figure A-1. System MTTF chart for nine reset and adjustment categories. Mark the MTTF's for Thyratron Ranging in '96 and '97/8 and Adjust Beam Voltage in '97/98 that have decreased dramatically because of increased intervention due to SLC/SLD operational demands for very stable modulator performance. This increase of the intervention rate is responsible for the lack of an increase in modulator reliability and availability in '96 and '97/8.

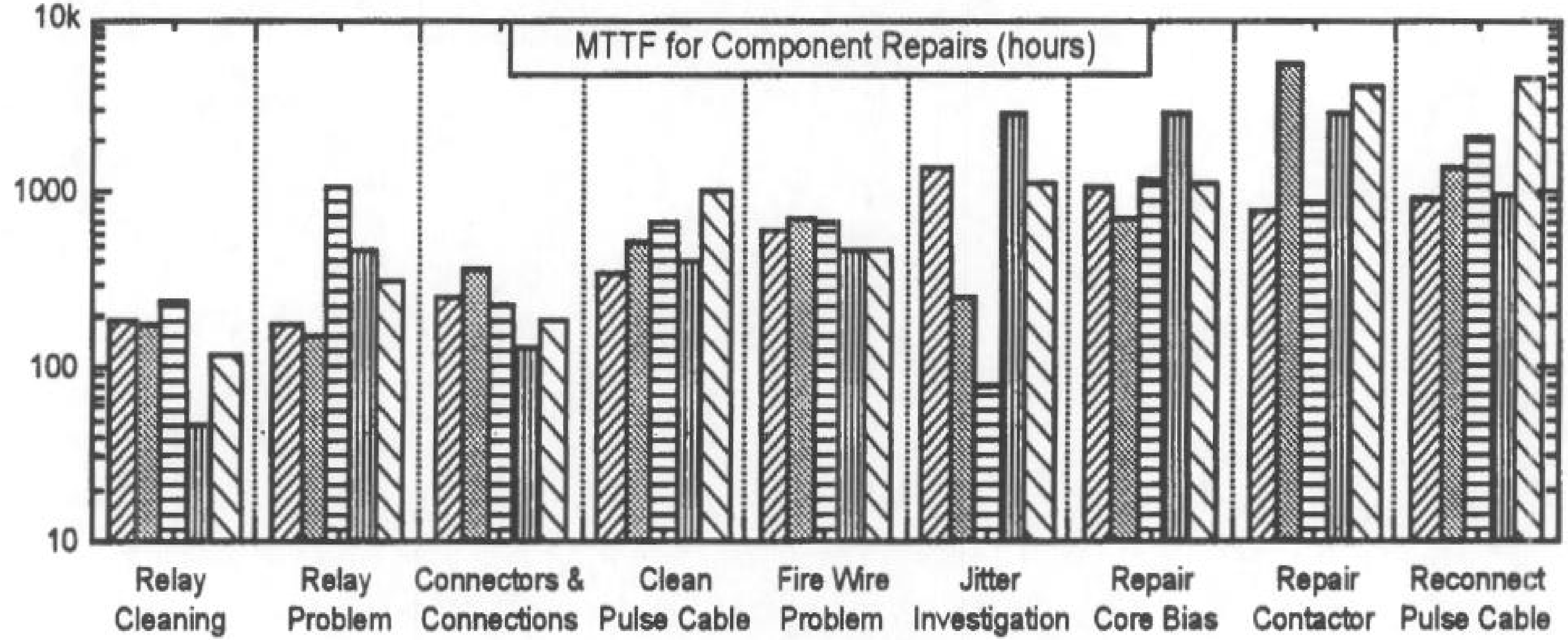


Figure A-2. System MTTF chart for repair categories. Notice that the MTTF values for repairs associated with the pulse cable (Clean and Reconnect Pulse Cable) have increased in '97/8 as a result of the anode reactor installation.

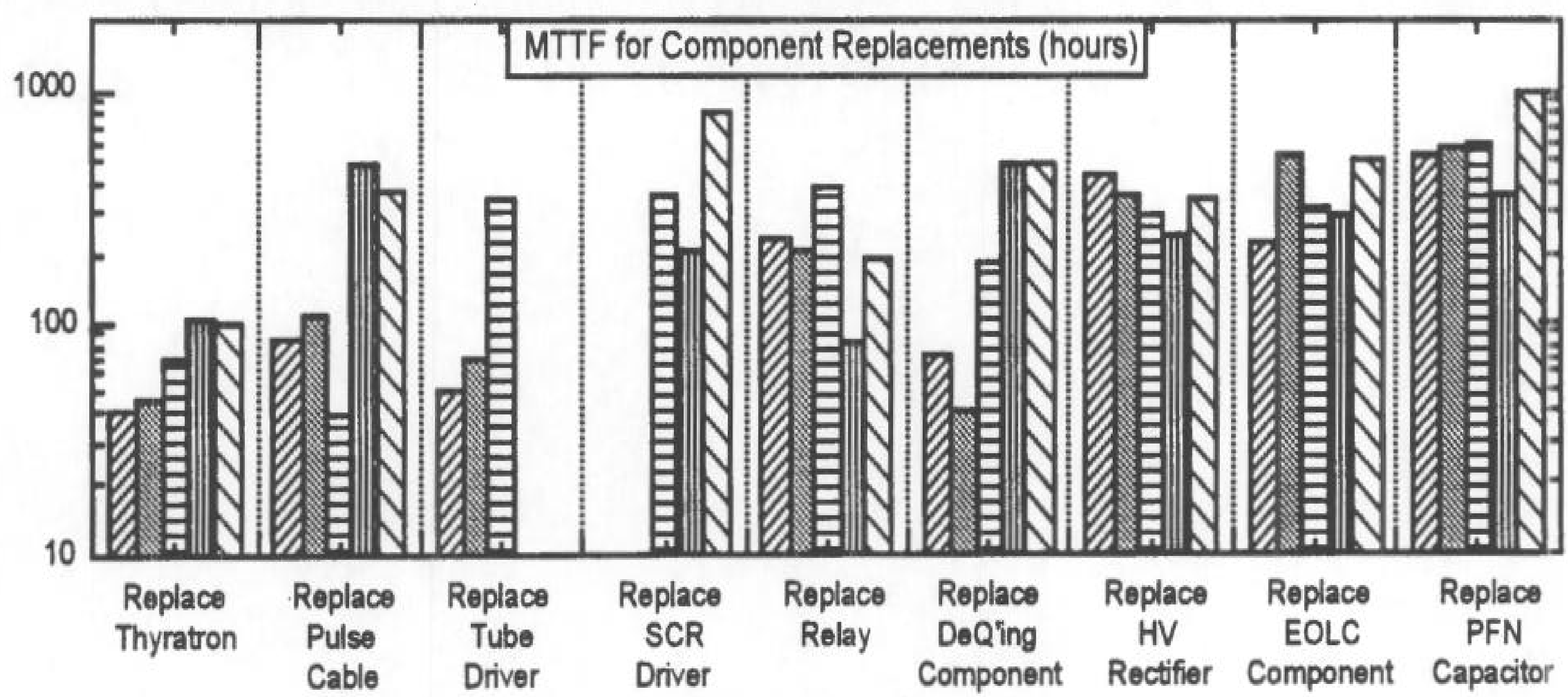


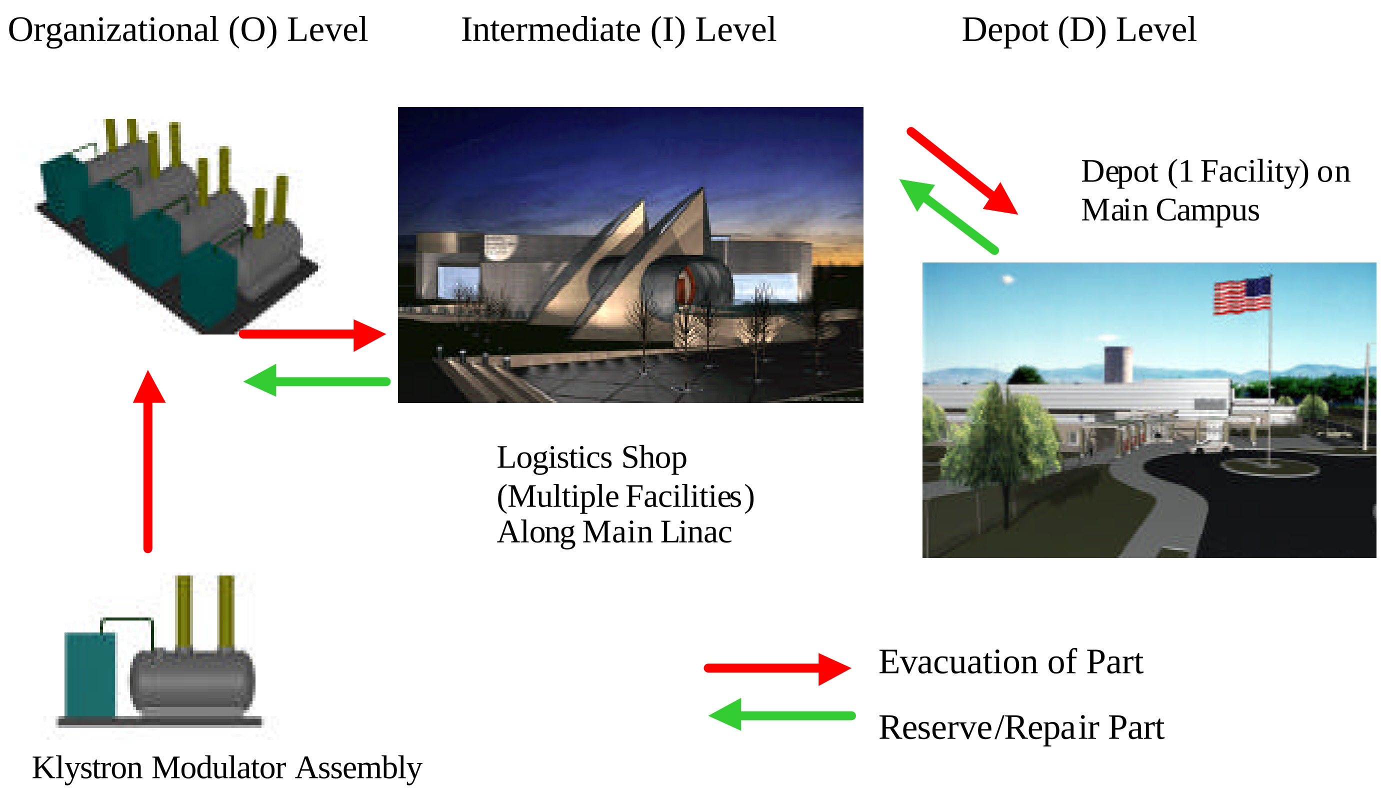
Figure A-3. System MTTF chart for nine component replacement categories. Regard the MTTF values for Thyratron and Pulse Cable replacements in '96 and '97/98 that have increased as a result of the anode reactor installation.

5. New Solid State Modulator System Estimated Availability

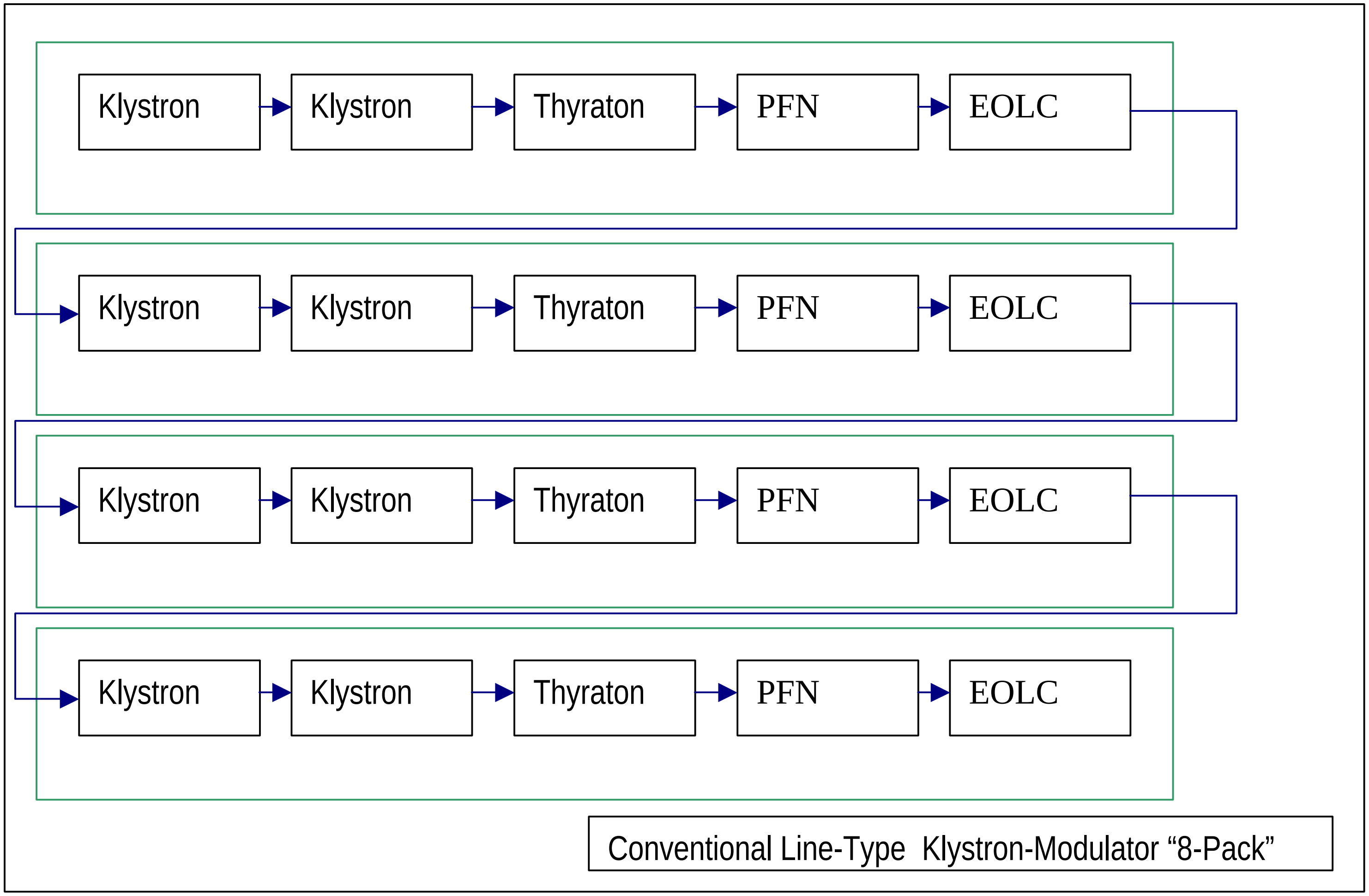
NLC Klystron/Modulator Availability, Z. Wilson, SLAC, ISE 2000 Presentation

O-I-D Maintenance Plan for Conventional Model

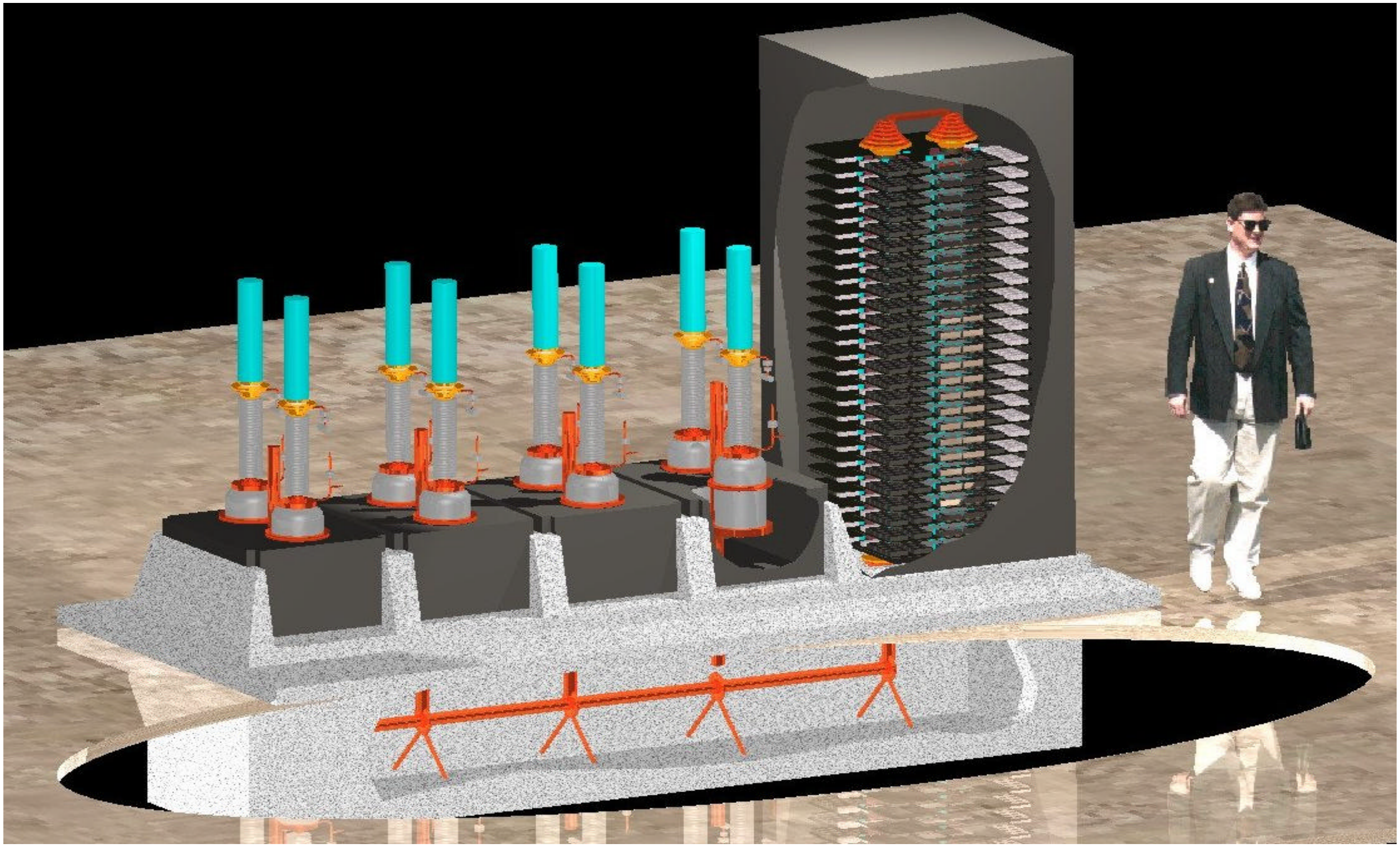
Reliability Engineering Management
O-I-D Maintenance Plan



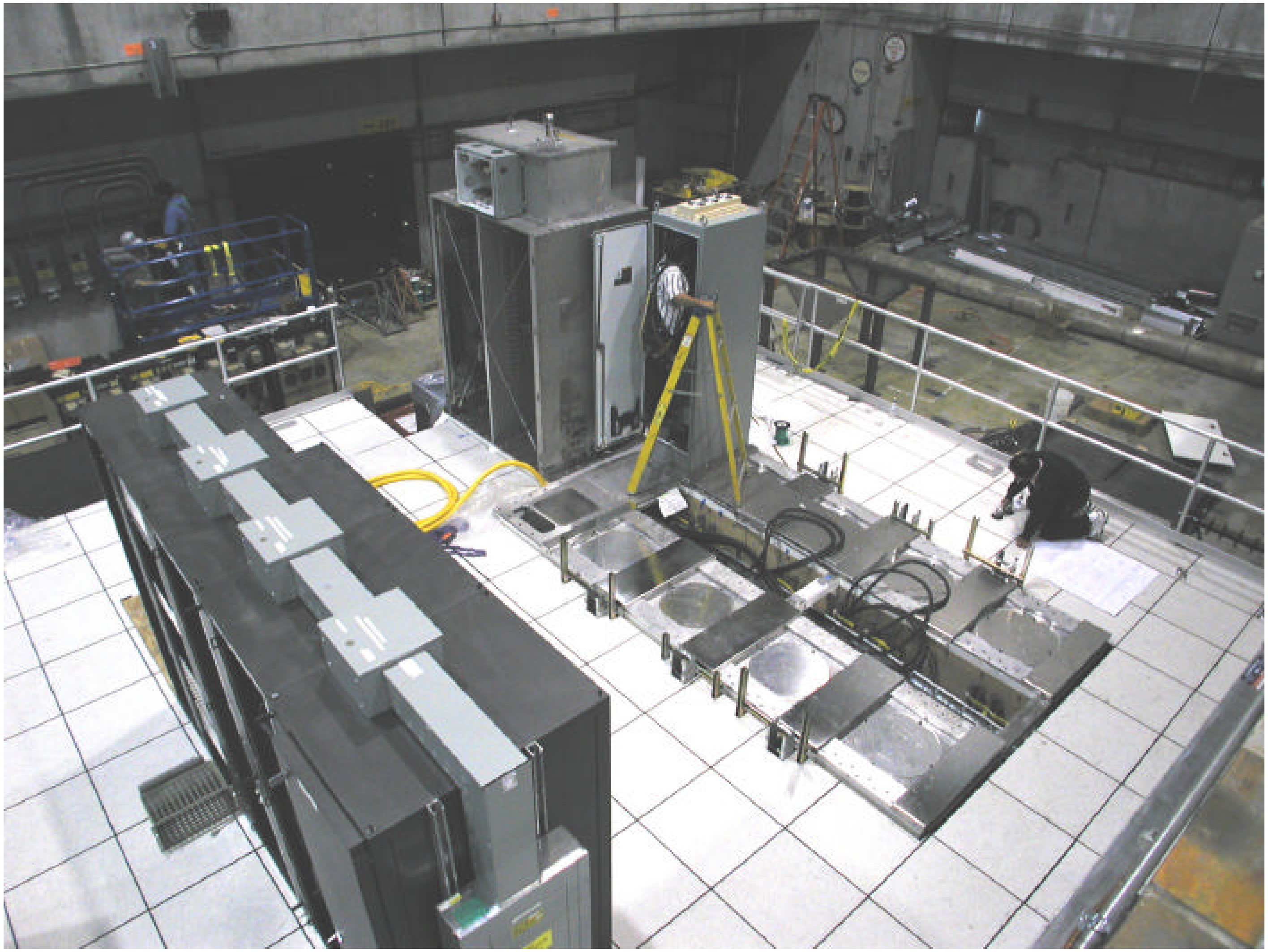
Klystron-Pulse Tank System RBD - Conventional



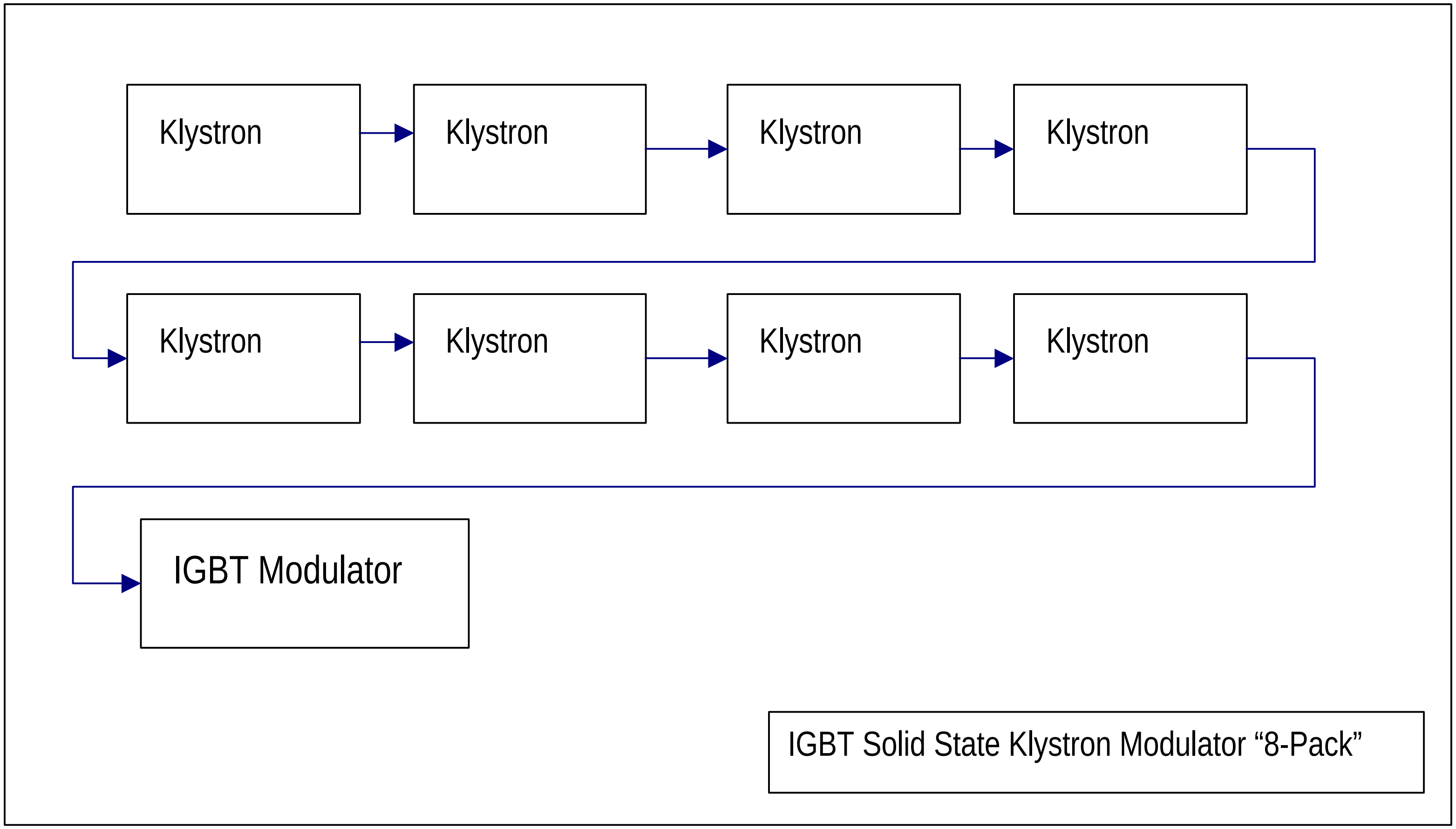
8-Pack Solid State Modulator Concept



8-Pack Under Assembly



Klystron-Pulse Tank System RBD – Solid State



Some Terms Used to Calculate Reliability/Availability

MTBF = mean time between failures	*(hr)*
λ = *failure rate* = $MTBF^{-1}$	(hr^{-1})
MTTR = mean time to repair/recover	*(hr)*
t = 9 month mission time = 6575 for LC	*(hr)*
Reliability = $e^{-\lambda t}$	*(none)*
Availability (A) = MTBF/(MTBF + MTTR)	*(none)*

Maintenance Model for Conventional Modulator

- For the Conventional Modulator we compute the MTBF for one Klystron Modulator Assembly as outlined below

Tube (2) MTBF	Thyratron MTBF	PFN MTBF	EOLC MTBF
$MTBF_{trans} := 20000 \cdot hr$	$MTBF_{thy} := 20000 \cdot hr$	$MTBF_{PFN} := 100000 \cdot hr$	$MTBF_{EOLC} := 150000 \cdot hr$
$\lambda_0 := \left(\frac{1}{MTBF_{trans}}\right) \cdot 2$	$\lambda_1 := \frac{1}{MTBF_{thy}}$	$\lambda_2 := \frac{1}{MTBF_{PFN}}$	$\lambda_3 := \frac{1}{MTBF_{EOLC}}$

$$MTBF := \frac{1}{\sum_i \lambda_i}$$

hours (MTBF for 1 X-Band Klystron Modulator Assembly)

$$MTBF = 6 \cdot 10^3 \circ hr$$

Maintenance Model for Conventional Modulator

$N_{500} := 1656$ Number of Klystron Modulator Assemblies X-Band for 500 GeV

$N_1 := 3312$ Number of Klystron Modulator Assemblies X-Band for 1 TeV

$MTTR := 2 \cdot hr$ This repair rate assumes complete swap-out, no in-place maintenance.

$A := \frac{MTBF}{(MTBF + MTTR)}$ $A = 0.9996667777$ Availablility for 1 Kly-Mod Assembly

$\lambda_{8pack} := 4 \cdot \lambda_{xband}$ $\lambda_{8pack} = 6.667 \cdot 10^{-4} \circ hr^{-1}$

$MTBF_{8pack} := \frac{1}{\lambda_{8pack}}$ $MTBF_{8pack} = 1.5 \cdot 10^{3} \circ hr$

Failure rate, MTBF, and Availability for the X-band "8-pack".

$A_{8pack} := A^4$ $A_{8pack} = 0.998667777$

Maintenance Model for Solid State Modulator

•For the Solid State case (5000V, 100 Core) Modulator the system is broken into the 8 klystrons it must drive and the modulator itself. For the calculation we have assumed 5 times better MTBF than the Conventional case. (Actual improvement is being researched now)

Tube (2) MTBF

$$MTBF_{trans} := 20000 \cdot hr$$

$$\lambda_0 := \left(\frac{1}{MTBF_{trans}}\right) \cdot 8$$

IGBT/Modulator System MTBF

$$MTBF_{igbt} := 250000 \cdot hr$$

$$\lambda_1 := \frac{1}{MTBF_{igbt}}$$

$$MTBF_{igbt} := \frac{1}{\sum_i \lambda_i}$$ hours (MTBF for 1 X-Band Solid State Klystron Modulator Assembly)

$$MTBF_{igbt} = 2.377 \cdot 10^3 \circ hr$$

Maintenance Model for Solid State Modulator

$N_{500} := 414$ Number of Klystron Modulator Assemblies X-Band for 500 GeV (IGBT)

$N_1 := 828$ Number of Klystron Modulator Assemblies X-Band for 1 TeV (IGBT)

$MTTR := 2 \cdot hr$ This repair rate assumes complete swap-out, no in-place maintenance.

$A := \frac{MTBF_{igbt}}{\left(MTBF_{igbt} + MTTR\right)}$ $A = 0.9991593739$ Availablility for 1 Kly-Mod Assembly

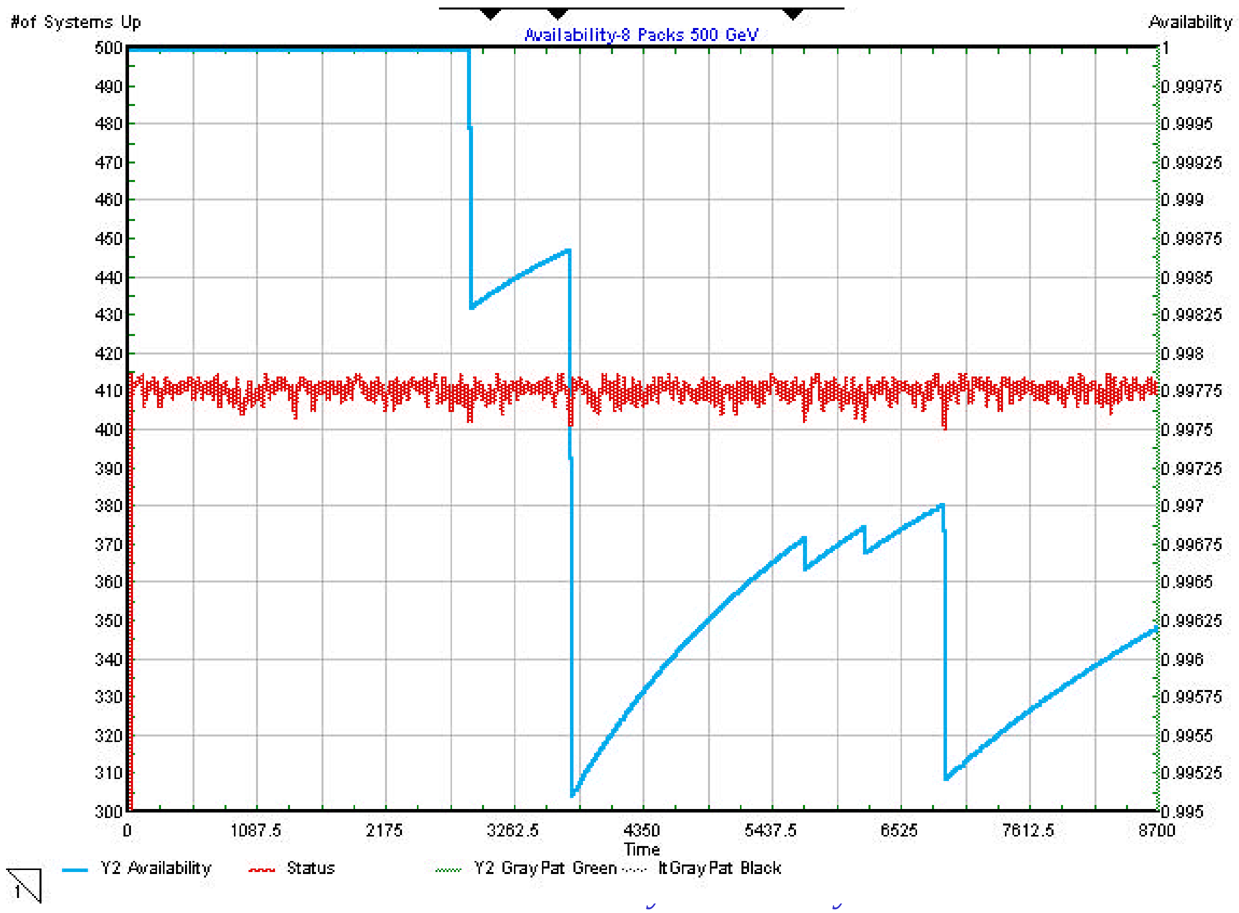
$\lambda_{8pack} := \lambda_{xband}$ $\lambda_{8pack} = 4.207 \cdot 10^{-4} \circ hr^{-1}$

$MTBF_{8pack} := \frac{1}{\lambda_{8pack}}$ $MTBF_{8pack} = 2.377 \cdot 10^{3} \circ hr$ Failure rate, MTBF, and Availability fc the X-band "8-pack".

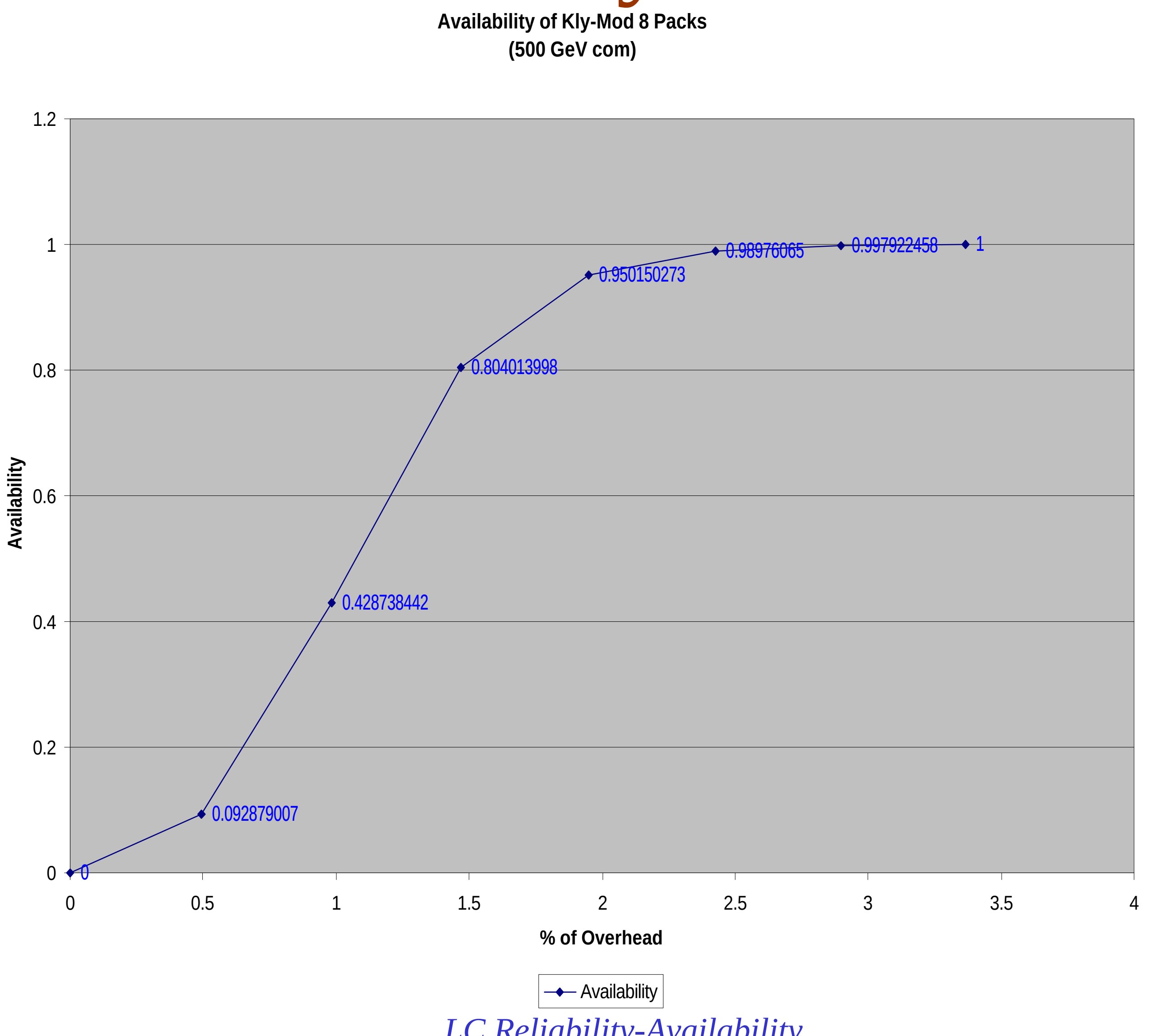
$A_{8pack} := A$ $A_{8pack} = 0.9991593739$

Simulation Monitor

- The red dotted line in the center of the graph shows the number of systems up or status of the main linacs.



ML Availability vs. Overhead

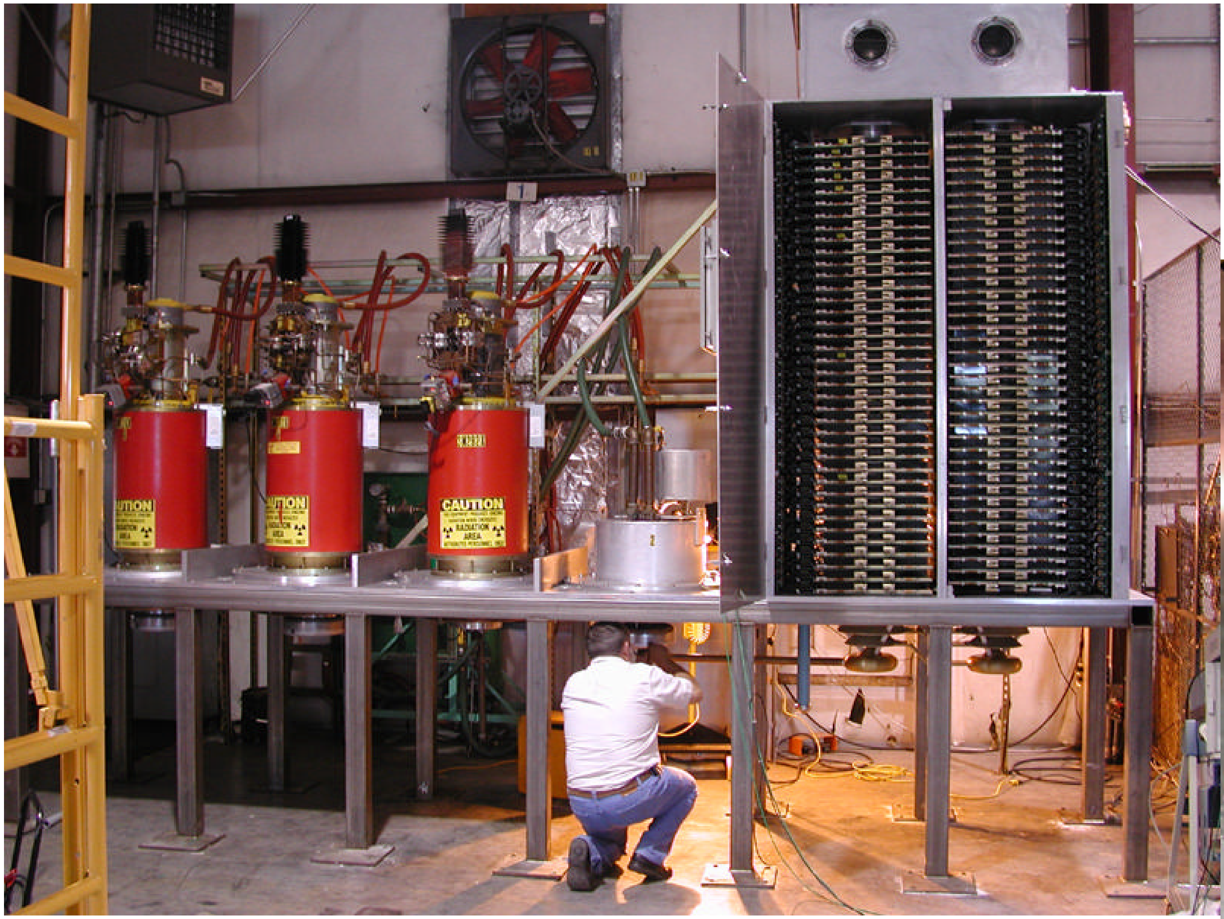


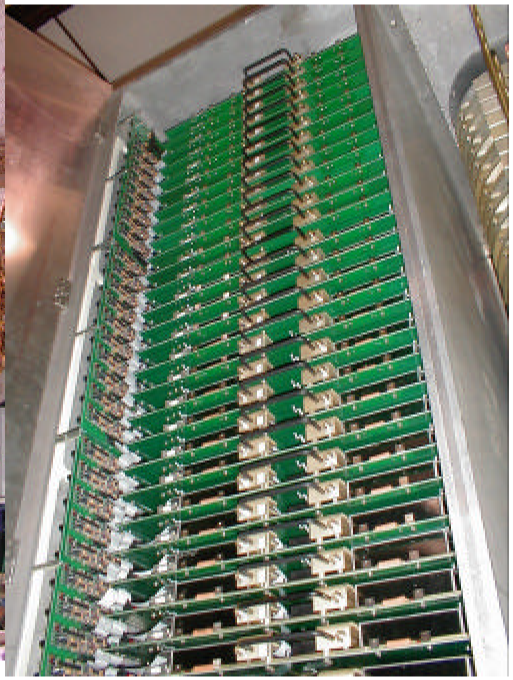
Summary Kly-Mod Availability

- Kly-Mod analysis needs updating.
  - Klystron performance dominates Availability.
  - Permanent Magnet klystron estimates suggest better lifetime, but no PPM tubes available yet.
- Solid State Modulator now well defined.
  - Prototype operating & being readied for running to near full load, 120 Hz.
  - Maintenance model can now be fully characterized.

8-Pack Prototype 500kV 2000A Pk

Shown set up to run 3-5045 S-Band Diodes + Water Load

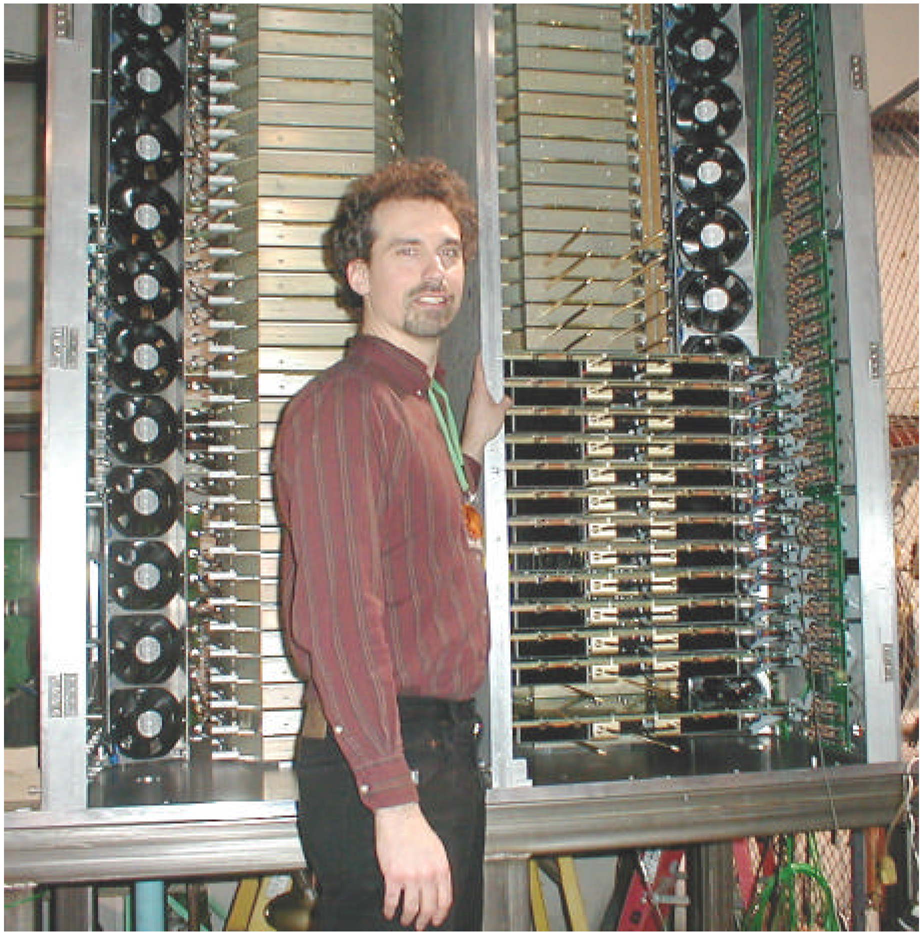




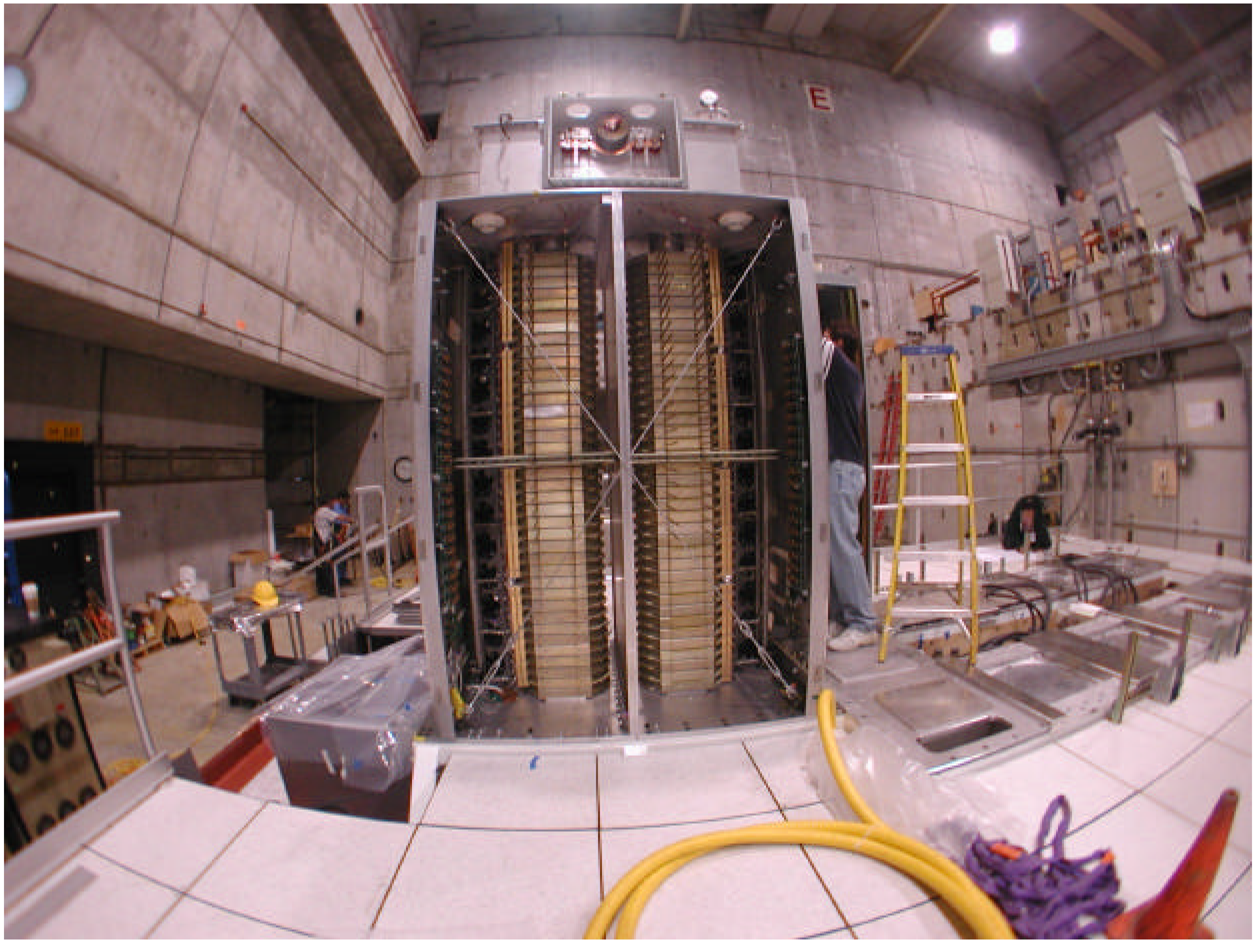
8-Pack 500kW 5kVDC Supply

IGBT Driver Board Construction

Core Stack & 1:3-Turn



SS Core Stack Newly Installed in 8-Pack Complex



8-Pack SS Modulator Design

- **Fractional Turn Primary with 76x2 driver boards in current unit, 2.2 kV each, and 3-turn secondary => 500kV, 2000A pk @ 1.6=>3.2 usec (1GW pk).**
- **76 Magnetic cores water cooled. (New unit oil cooled.)**
- **500 kW DC Buck Regulator power supply.**
- **Boards are at ground potential for easy swapping.**
- **4-6 Extra boards built into stack for redundancy.**
- **Adjust voltage, continue operating with failures.**
- **Failed boards can be monitored through control system & replaced opportunistically.**

Other Features

- Unit can drive 8 - 75 MW klystrons at adjustable pulse width out to 3.2 usec.
- Modular design adaptable to other configurations such as 2-Pack for Injection linacs.
- Unit can run at reduced power with a failed klystron if necessary. This has not been worked out in klystron availability model.
- Current assumption is 2.5% redundancy of complete 8-packs in system.

SS Modulator Availability

- In principle, SS stack could operate over full mission of 6575 hours without intervention.
- Modular design makes MTTR board swapping <<2 Hrs.
- System operates at low voltage (5kV max) unlike present units 40 kV or more.
- Weakest point in terms of MTBF is the large DC power supply.
- Need to create modular design for quick repair of the 500 kW PS.

Klystron-Modulator System Availability

- Klystrons and 500 kW power supply will dominate availability model.
- More work needed to develop extremely quick replacement, minimum exposure of oil & vacuum parts to air.
- Exposing klystron tank oil to air during replacement incurs a long recovery period of pumping air out of oil.

Discussion

- Availability is the ultimate measure of machine performance. (*When trying to catch fish, the hook must be in the water, not caught in your pants.)*
- All systems in current machine designs require strong maintenance support to achieve reasonable availability.
- Current models examined DO NOT meet the desired requirements for an LC as outlines in the NLC model of 85% system availability.

Discussion cont'd.

- The more components in the machine the more difficult to achieve high availability. SSC and VLHC models used 65%, and required considerably lower MTTR than current designs having higher availability.
  - Ref. *Reliability/Availability considerations for a VLHC*, J. Dugan, Cornell (undated).
- Availability goal of 85% seems aggressive cf. current linacs but Light Sources are pushing into high 90's. Enormous Opportunity Cost suggests we should set a goal of ~95% and study ways to achieve it.

Discussion cont'd

- Design Impact
  - Design all system components for ease of diagnostics & replacement (Do not look to car manufacturers for advice on this one).
  - Consider adding redundancy in critical elements where benefits are significant.
  - Consider Opportunity Cost as a *real* cost and argue for additional development funds where reliability gains can make a major difference in up-time.